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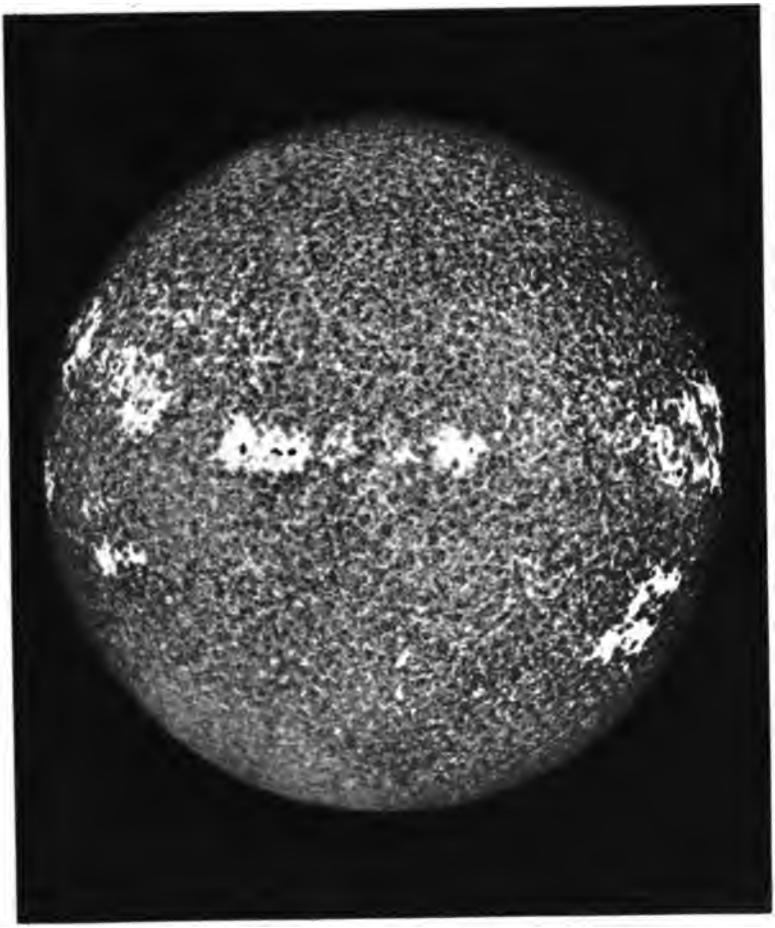
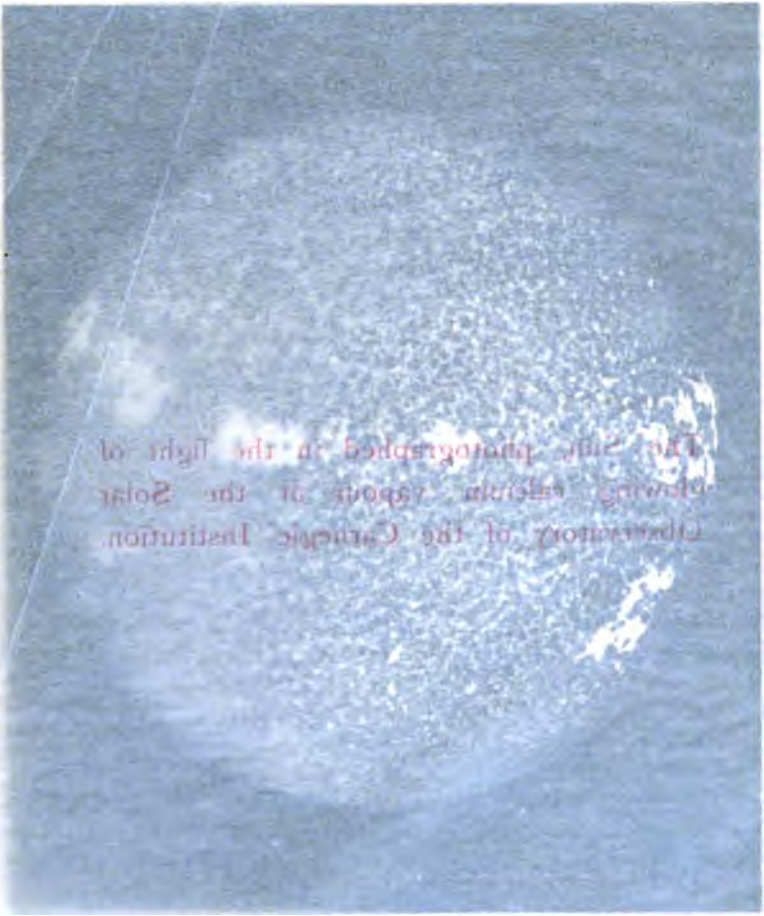
THE SOLAR SYSTEM



The Sun, photographed in the light of glowing calcium vapour at the Solar Observatory of the Carnegie Institution.



The Solar System

A Study of Recent Observations

By

Charles Lane Poor

Professor of Astronomy in Columbia University

Illustrated

G. P. Putnam's Sons
New York & London
The Knickerbocker Press
1908

The Knickerbocker Press, New York

PREFACE

THIS work grew out of a series of lectures delivered at Columbia University. Intended for the general student, these were mainly historical and were used to supplement standard text-books and to guide the students in their reading. An attempt was made to present the subject in untechnical language and without the use of mathematics; to show by what steps the precise knowledge of to-day has been reached, and to explain the marvellous results of modern methods and modern observations.

The subject of the present volume, the Solar System, covers such a wide field that, in order to keep within reasonable bounds, many interesting subjects had to be omitted. To this may be attributed the rather scant mention of many important matters and the entire elimination of others. Eclipses of the sun, the most impressive of astronomical phenomena, have been passed over with but brief mention in connection with the study of solar physics. On the other hand considerable space has been devoted to the Tides and to Tidal Evolution, subjects but briefly treated in most astronomical works.

Mars has been given more space than the subject

really warrants. But so much has been written about the so-called Martian Canals and such attractive conclusions drawn from the observations, that a rather full discussion of even the most radical hypothesis does not seem to be entirely out of place in the present volume. Certain highly imaginative and exceedingly popular ideas in regard to this planet have attained such prominence and are supported with such a mass of apparently valid observations, that they cannot be dismissed with a word. Observations made and theories advanced in good faith deserve courteous and careful consideration.

The author is indebted to Professor Harold Jacoby and to Dr. S. Alfred Mitchell for valuable suggestions. Dr. Mitchell read the manuscript, revised the proof, and aided in the selection of the illustrations. To him are due most important criticisms, notes, and suggestions, especially in the treatment of the astrophysical problems. The author desires to express his sincere appreciation of this assistance.

C. L. P.

October, 1907.

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THE SOLAR SYSTEM

CHAPTER I

THE MOON

TO the inhabitants of the earth, the moon among all the heavenly bodies is second only to the sun in importance. In brightness she far outshines all the stars, and her conspicuous phases give her apparently a unique position in the starry heavens. From prehistoric times, the moon has been an object of wonder, of admiration, and of worship, has inspired poetry, love, and gross superstition; her phases have regulated the festivals of the Church and have given us two of our principal divisions of the calendar, the month and the week. To the moon, principally, are due the tides, the ever-fluctuating motions of the ocean. The very beginnings of astronomy seem to have originated in the study of her phases, her motions, and the phenomena she causes. Important, however, as the moon is to us, yet she is one of the least among the heavenly bodies; she is but an attendant of an attendant of one of the lesser suns among the myriads that form the universe.

The most striking and most conspicuous phenomena connected with the moon, which even the most ignorant and casual observer must note, are the phases. The moon first appears as a thin crescent of light; but night after night, this crescent broadens out, gives place to a semi-disc, and this gradually widens till there appears a full and complete circle of light. This in turn wanes, the disc becoming a semicircle, then a crescent, until finally the moon disappears from sight; only to reappear, however, and to go through again its cycle of phases. Once every 29.5 days is this series of phases repeated; the month of 30 days is thus a natural division of time and was introduced into the calendar in prehistoric times. The early Greeks used a calendar based entirely upon the moon, Hesiod making a year consist of twelve months, each of 30 days.

Ever since recorded history it has been known that the moon is a small, solid, spherical body revolving about the earth as a centre. Plato, who flourished about 400 B.C., knew that the moon shines by reflected light, and but a little later Aristotle gave a full and complete explanation of the monthly phases. Not only was the moon thus early known to be an opaque, spherical body, shining by reflected sunlight, but it was known that it is the nearest of our celestial neighbors. That it is nearer than the sun was obvious from solar eclipses; for it was early recognised that such eclipses are caused by the moon passing between us and the sun, and thus cutting off the light of the

sun. Aristotle showed, in a similar manner, by noting occultations (passages of the moon in front of celestial objects) that the moon is nearer than Mars and nearer than many of the fixed stars.

Thus many centuries ago the shape, size, and distance of the moon were fairly accurately known; her motion about the earth was recognised, as well as the cause of her phases and the general characteristics and phenomena of eclipses. Modern observations and methods, aided by the most delicate apparatus, have changed somewhat the numerical values determined by these ancient astronomers, but no error has been found in their fundamental ideas, though their roundabout and ingenious methods are no longer necessary. The instruments of to-day are so delicate and their measures so precise that the distance of the moon can now be found directly from her parallax. This method of finding the distance of a heavenly body is fundamental to astronomy and a brief explanation of its principles may not here be out of place.

Parallax is a technical name for a very simple and every-day matter. From a window of Fayerweather Hall, Columbia University, the chimney of the power house appears in the north-west, from a window in the Library, the same chimney appears nearly due north: the apparent direction of the chimney will thus be changed by an observer passing from Fayerweather to Library. This change in the apparent direction of the chimney, caused by a real

change in the observer's position, is what is called "parallax." Now, further, if the exact number of feet through which the observer has moved in passing from window to window and the exact directions in which the chimney appears from the two windows are known, then by simple geometry can be found the distance of the chimney from either window. This same principle is used in surveying, in measuring the distance across a river or an impassable swamp. It is the only method by which the distance of an unreachable body can be measured: it is the method by which every one judges the distances of various objects. From babyhood one's eyes are trained to solve, unconsciously, and without apparent mental effort, the problem of parallax, of angle and distance.

In astronomy the parallax of a body, the moon for instance, is the difference in direction in which it is seen by an observer, or observers, in two different positions, and the parallax bears different names, according to the different positions of the observer and the body. As the moon, at a given instant, appears to an observer in Greenwich, England, in one direction, to an observer in New York in a second direction, and to one in Washington in still a third direction, it becomes necessary to have some standard place to which the position of the moon can be referred. The nautical almanacs give the position of the moon in the heavens for every hour of every day, but as every observer sees it in a different direction, no book

would be large enough to print all the different directions in which it might be seen from every point on the earth's surface. Instead there is printed the position in which it would be seen at every hour, by an observer in the standard locality. The easiest place to take for this standard, the place over which there can be no international complications and jealousy, is *the centre of the earth.* The position of the moon, or of any other body, as it would be seen by an hypothetical observer at the centre of the earth is called its *geocentric position;* the position in which a real observer on the surface of the earth actually sees the moon is called its *apparent place,* and the difference in direction between these two places is called the *geocentric parallax,* or more commonly, simply the parallax.

To find the distance of the moon from the earth it is only necessary to select two observatories as widely apart as possible, but very nearly in the same longitude (Berlin and the Cape of Good Hope for example), and to have observers at the two places determine the position of the moon in the heavens at the same instant. Then, as the size of the earth has been accurately measured, the distance apart of the observers is known; and this distance, together with the observed directions of the moon, give all the data necessary to find by simple trigonometry the distance of the moon. This is shown in the following diagram, in which the observers are supposed located at B and C, and the moon

at M. In the triangle B M C, the side B C is known, for it is the distance apart of the two observatories, the angles M B C and M C B are readily found from the measured positions of the moon. Hence in this triangle two angles and the included side are known,

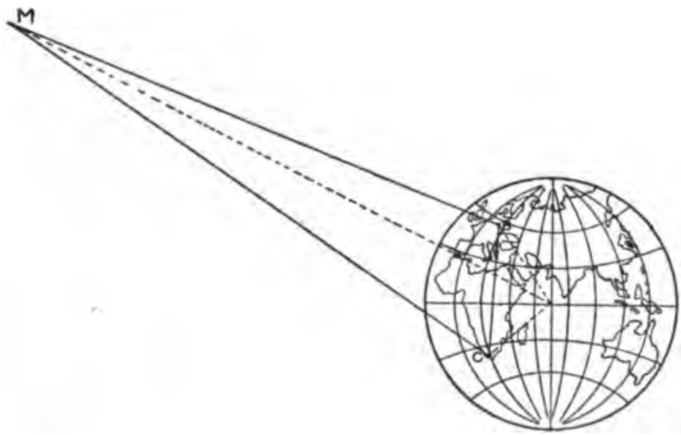


FIG. 1. THE DISTANCE OF THE MOON.

and from trigonometry there can be found at once all the other parts of the triangle. As soon as the side B M is thus known, the distance of the moon from the centre of the earth, O M, can be calculated.

With the delicate instruments of to-day the direction in which the moon appears can be determined to within a second of arc, and the distance of the moon from the earth found to within 10 or 20 miles. It is hardly correct, however, to speak of the distance of the moon from the earth, for this distance is continu-

ally changing; gradually growing smaller until a certain limit is reached, then increasing and finally decreasing again. The average distance of the centre of the moon from the centre of the earth is 238,840 miles. In this figure there is a possibility of error of only 20 units, or one part in twelve thousand. The maximum and minimum distances of the moon are given by Neison as 252,972 and 221,614 miles.

The fact that the distance of the moon from the earth varies shows that her orbit about the earth is not circular, as was supposed by the ancient astronomers. At the time of Hipparchus (second century B.C.) it was known that the distance between the two bodies is continually changing. In explaining this he still considered the orbit circular, but thought that the earth was not situated at the centre of the circle. It was not until Kepler enunciated his celebrated laws of motion, that the true form of the moon's path was known. The moon travels about the earth in an ellipse, and the earth is situated at one focus of this ellipse, not at its centre. The eccentricity of the ellipse varies between $\frac{1}{15}$ and $\frac{1}{21}$, averaging about $\frac{1}{18}$. The point of this orbit at which the moon approaches nearest to the earth is called the *perigee;* that at which the moon is farthest from the earth is called the *apogee,* and the imaginary line passing through these two points is called the *line of apsides.* The line of apsides is thus the major axis of the elliptical orbit of the moon. Around this elliptical orbit

the moon travels eastward, and completes a circuit in 27d. 7h. 43m. 11.55s. (27.32166 days), and this is the *sidereal* or true month. In this time the moon completes one circuit of the heavens, apparently passing *from a given star back to the same star again.* This, however, is not the ordinary or common month, which is counted from new moon to new moon, or from full moon to full moon, and is technically called the *synodic* month.

This eastward motion of the moon in her orbit causes a very striking phenomenon: the retardation of the moon's daily rising and setting. We have all noticed how the full moon rises in the east about an hour later each night. If she rises at eight o'clock to-night, it will be nearly nine o'clock to-morrow evening before she appears above the horizon. The average value of this daily retardation is 50½ minutes, but the actual retardation is extremely variable, depending upon the latitude of the observer on the earth and the position of the moon in its orbit on the day in question. In New York City the retardation varies from 23 to 77 minutes, in latitudes above 61° 20′ the retardation sometimes exceeds 24 hours, that is, there are some days in which the moon does not rise at all and some days in which it is always above the horizon, travelling about the sky in a circle, which does not quite touch the horizon at the north point.

This variation in the daily retardation of moonrise causes what are known as the *harvest* and the *hunter's* moon: the harvest moon being the full moon which

comes nearest to the autumnal equinox (Sept. 23); the hunter's moon being the next following full moon. The orbits of the earth and moon happen to so lie that at this season of the year the daily retardation of moonrise is the least, and the moon will rise for several consecutive nights at nearly the same hour, so that the moonlight evenings last for an unusual length of time, and the harvesters and hunters take advantage of these bright evenings.

The Physical Characteristics of the Moon. The diameter of this attendant of the earth, which is of so much practical value to us in giving light by night and in regulating the tides, is a little more than one quarter that of the earth—according to the latest measurements, is 2163 miles. Since the surfaces of spheres are proportional to the squares of their diameters, and their volumes proportional to the cubes, it follows that the surface area of the moon is about $\frac{1}{14}$ and the volume $\frac{1}{49}$ that of the earth. The total surface of the moon is, therefore, almost exactly equal to the combined areas of North and South America, a little less than four times the area of the United States, if we include Alaska, but exclude the island possessions acquired in the war with Spain. The actual surface area of the moon's hemisphere which can be seen at any one time is about equal to the area of North America. The surface conditions of our satellite, its mountains and valleys, can best be studied when the moon is half full, and at that time its illuminated and visible area is almost exactly equal to

that of the United States; the distance from horn to horn on the moon being 3396 miles, while from Maine to California the distance is 3100 miles.

Certain portions of the moon's surface have never been seen and must always remain invisible to the inhabitants of the earth. Long before the invention of the telescope, it was known that the dark markings on the moon's surface, " the man in the moon," always remain in the same relative position, that the moon always points the same face towards the earth. We see to-day precisely the same half of the moon's entire surface as did Aristarchus, or as did Galileo with the first telescope. This fact that we always see the same portions of the moon's surface is due to the peculiarity of its rotation.

Just as the earth rotates on an axis once in 24 hours, thereby causing the alternation of day and night, so the moon rotates on an axis, whirling about through space just as a top spins upon the floor. But the moon rotates about her axis very much more slowly than a top, much more slowly than the earth, leisurely making one rotation in a sidereal month. Thus it happens that the moon rotates on her axis in exactly the same time as it takes her to revolve in her orbit about the earth. It might seem, at first sight, that the moon does not revolve. That it does revolve may be seen if we compare the motion of the moon about the earth with that of an apple tied with a cord and swung round and round. The stem of the apple to which the string is tied always points toward the hand

just as the face of the man in the moon is always turned toward the earth. It is evident that the apple does actually rotate, for if we swing it about our head in a horizontal circle the stem will present itself in turn to every point of the compass.

FIG. 2. THE LIBRATIONS OF THE MOON. FROM "THE MOON" BY R. A. PROCTOR

Now while on the average the moon keeps the same face towards the earth, still its motion is not exactly like that of the apple at the end of a string. There is no rigid attachment like the string, connecting the moon and the earth, and the rotation on the axis and

the motion in the orbit about the earth go on independently of each other. The motion of rotation is uniform, the motion in the orbit is not. Thus while the moon completes one rotation on its axis and one revolution in its orbit in 27.5 days, it does not cover one quarter of its cycle in one quarter of this time (6.9 days). It sometimes moves faster and sometimes more slowly in its orbit and will thus present slightly different faces towards the earth. A mountain which at one time might appear to be exactly in the centre of the moon's disc, at another time will appear slightly to right or left of the centre. These slight *librations,* as they are called, allow us to see a little more than one half the surface; there is a little ring or fringe around the edge of the moon which is alternately brought into view and concealed. The whole surface of the moon can be divided into three parts; one portion, about $\frac{5}{12}$ of the whole, is always visible, another of equal extent is never seen, while the third portion, amounting to about $\frac{1}{6}$ of the whole, is alternately swayed out of and into view.

The exact agreement between the periods of rotation and of revolution of the moon is not accidental, but is the direct result of some physical condition. It is possible that the moon is not exactly spherical, being more of an egg shape, with a relatively large bulge on one portion of her surface. Such a shape, in which the centre of figure does not coincide with the centre of gravity, would account for the agreement between the lunar day and the sidereal month.

The physical conditions existing on the moon's surface were early a source of speculation. As early as 500 B.C. Anaxagoras regarded the moon as an inhabited world, similar in all respects to the earth. The large dark markings, which are known to every one from childhood, he regarded as seas and oceans, and he thought her surface diversified with hills and valleys. Other writers considered the moon as a smooth mirror-like body, in which were seen the reflected images of the seas, mountains, and valleys of the earth. Plutarch, accepting and following the ideas of Anaxagoras, recognised the presence of mountains in the moon, explaining by the irregularities of the surface and the shadows cast by the mountains the rough, broken edge which always separates the light from the dark portions of the moon.

A radical change was introduced into physical astronomy when, in May, 1609, Galileo saw the moon through the first telescope ever used for astronomical purposes. His largest telescope was little more than a high-powered field-glass, magnifying to the paltry amount of some thirty times, yet with it he recognised the main features of the moon's surface. He found her surface covered with cup-shaped mountains, rings of high land surrounding central depressed areas, and he showed clearly how the heights of the mountains could be measured. Near the ragged line which separates the light and dark portions of the moon and just within the dark part are often seen brilliant white points. These points are the tops of

mountains lighted up by the rising sun long before it shines upon the level plains at their foot. The distance at which an object can be seen at sea depends upon its height above the surface of the earth. As a vessel approaches the land the high hills first become visible, then the lower portions, and finally the shores and beaches. Lighthouses, which are to be visible at great distances, are made very high. From a simple geometrical formula, the distance at which an object will be visible can readily be calculated if its height is known; or, if the distance at which an object is visible be known, its height can at once be found. So with the moon, the distance from the bright mountain top, just touched by the rising sun, to the line on the level plain which separates day from night, is the distance at which the mountain would be visible to a lunar inhabitant. This distance Galileo measured, and from it calculated the height of the mountain. Several of the lunar mountains are thus found to be nearly seven miles high, far higher in proportion than any mountains of the earth.

For many years after the time of Galileo students of the moon still considered the darker portions of the surface as seas and the lighter coloured parts as continents. Hevelius adopted this view and constructed a chart, showing the location of the principal objects on the moon's surface. His *Selenographia,* containing this chart, appeared in 1647, and in this work he assigned names to the mountains, seas, islands, continents, and bays. This chart, of course,

The Full Moon from a Photograph Taken by L. M. Rutherfurd, June 2, 1871

was extremely rough and imperfect as compared with those of to-day. His telescope was small and weak and he had no method of locating the various markings on the surface, excepting mere eye estimations.

From this time on the surface of the moon was an object of constant study and many charts were drawn and published during the next century. The first really reliable chart was that constructed by Tobias Meyer, and published at Göttingen in 1775, thirteen years after his death. The fact was gradually recognised that there is no water on the surface and that the so-called seas and lakes are really but different coloured rock formation; just as in New Jersey we have the bright, light sands of the coast, and the deep, dull red clay and mud of the interior.

The old idea that the moon was an inhabitable world, similar to the earth, died very hard, and as late as 1835 was revived in what proved to be the greatest scientific "hoax" of the century. In 1833 Sir John Herschel, the greatest observing astronomer of the age, left England for the Cape of Good Hope. Up to this time there had been no telescope in the southern hemisphere and Herschel planned to study at the Cape those portions of the heavens that are invisible from Europe. For this purpose he took with him a collection of astronomical instruments, including the largest telescope then in existence. On arriving at the Cape he set up his instruments and proceeded quietly with his programme.

In 1835, the New York *Sun* published a series of

articles, alleged to be taken from the Edinburgh *Journal of Science* and purporting to give an account of "Great Astronomical Discoveries, lately made by Sir John Herschel at the Cape of Good Hope." Herschel was represented as having had constructed in England, prior to his departure, a new and wonderful telescope of undreamed-of magnifying power. So powerful, indeed, was this instrument that it brought the smallest details on the moon into clear view. The pseudo-optical and mechanical principles upon which the telescope was constructed were explained in a mass of technical jargon, which was absolutely absurd and meaningless to a scientist, but which left the ordinary reader with the idea that a wonderful invention had been most clearly explained.

The first time this imaginary instrument was turned upon the moon, Sir John, according to the *Sun*, saw the most wonderful sights. There were seas, lakes, rivers, and forests, "fairer shores never angels coasted on a tour of pleasure." Animal life was abundant, herds of small cattle or bison grazed on the fertile plains, wild animals were seen, and finally were discovered angel-like human beings. To quote from the original. "Whilst gazing in a perspective of about half a mile, we were thrilled with astonishment to perceive four successive flocks of large-winged creatures, wholly unlike any kind of birds, descend with a slow, even motion from the cliffs on the western side, and alight upon the plain. . . . Certainly they were like

human beings, and their attitude in walking was both erect and dignified."

These articles almost completely deceived the press of the United States, and were extensively copied, Sir John Herschel being lauded on all sides for his great invention and epoch-making discoveries.

The statements attributed to Herschel are as far from the truth as possible. Instead of being an inhabitable world, with land and water, trees and forests, the moon is an arid waste, a dead body, with no water and without sensible atmosphere. It cannot be asserted that there is no atmosphere, but only that, if any atmosphere exists, it must be extremely rare, and that its density cannot exceed $\frac{1}{750}$ that of air at the earth's surface. Our atmosphere produces a barometric pressure of 30 inches, the moon's cannot produce a pressure greater than $\frac{1}{25}$ of an inch, or one millimetre. A column of our atmosphere one inch in cross section and reaching from the surface of the ocean to the highest point weighs about fifteen pounds; such a column of the moon's atmosphere cannot weigh more than one quarter of an ounce.

There are many ways in which this lack of a sensible atmosphere can be shown. The telescopic appearance of the mountains is nearly conclusive proof on this point. The edges of the craters, the details of the surface are always seen clear and sharp, the shadows are jet black, no haze, clouds, nor storms have ever been observed. When the moon passes across the face of the sun in a solar eclipse, the edge of the

moon always appears a clear-cut, sharp line; while if there was an atmosphere the light of the sun would be refracted through it and the moon would appear as though surrounded by a halo. When Mercury passes across the face of the sun, her dense atmosphere shows a dusky ring surrounding the planet. Again this absence of a refractive atmosphere is shown when the moon occults, or passes in front of, a star. If the moon were surrounded by an atmosphere, it would act as a lens and bend the light from the star out of its path, and render the star visible for a short time after it was really behind the edge of the moon. Thus the time during which the star would be concealed would be sensibly diminished, and the amount of such diminution of time would depend upon the density of the atmosphere. As the rate of motion of the moon among the stars is known, the time it should take it to pass before a given star can easily be calculated. Repeated measures of the length of time during which such occultations last, have shown that there is no appreciable diminution from the calculated time, and that, therefore, there is no appreciable atmosphere.

If there be no atmosphere on the moon, there can, of course, be no *liquid* on the surface, for any such liquid would evaporate under the influence of the sun's heat, and at once give rise to an atmosphere. There being no atmosphere on the moon, there is nothing to temper the alternate changes from light to darkness, and from heat to cold. On the moon there is no phe-

nomenon like our twilight; the sun rises suddenly, and dark night passes instantly into the full sunshine of a long lunar day. The rocks are exposed to the full glare of the sun for fourteen days, and during this time the heat of the sun beats down upon the surface without any breeze to cool it, without any passing cloud to give momentary relief. The surface of the moon must, it would seem, become extremely hot, must be baked with a heat in comparison with which that in the Desert of Sahara would seem like the polar regions. Yet according to the researches of Langley the temperature of the moon's surface, when the sun is in the zenith, is below the boiling point of water, but far above the freezing point.

Suddenly the sun sinks below the horizon and the long lunar night of fourteen days is begun. The rocks radiate forth into space the heat they have acquired from the sun, and the temperature falls, and falls frightfully low. The temperature of the night side of the moon approximates toward that of interplanetary space, toward the absolute zero, 460° below the ordinary zero as marked on our common thermometers.

The surface of the moon is literally covered all over with mountains, or pitted with craters. The mountains on the earth are arranged in groups and ranges, with broad level plains and oceans between; but not so the mountains of the moon, they are scattered all over the surface, packed together, without

any definite arrangement or formation. These mountains are great cup-shaped craters, resembling, but greatly exceeding, the great volcanic craters of the earth. The largest terrestrial crater does not exceed seven miles in diameter; some of those on the moon exceed one hundred miles, while the number of

FIG. 3. COMPARISON OF LUNAR VOLCANOES WITH VESUVIUS AND THE VICINITY OF NAPLES.

those which exceed seven miles can be counted by hundreds.

The general resemblance of the lunar mountains to the volcanic areas of the earth's surface is shown by a comparison of the lunar surface with a relief map of southern Italy. Vesuvius appears as a huge cone surrounded by a ring-like mountain, known as Monte Somma; while several extinct craters without the

central cone more strongly resemble the lunar volcanoes. According to W. H. Pickering the craters of Kilauea and Mauna Loa, on the island of Hawaii, are more nearly characteristic of the lunar type. The rims of these craters are extremely rough and are intersected by cracks and faults, and each large crater is accompanied by smaller ones, which partially destroy the symmetry of the large ring. These Hawaiian volcanoes present every feature that can be found in their lunar counterparts.

Although the volcanic origin of the lunar craters is almost self-evident, yet other theories have been advanced. Proctor suggested a meteoric origin; the craters being the holes left by meteors falling upon the yet plastic surface. This and other equally far-fetched theories have received little or no support and the volcanic character of the lunar mountains is practically established.

The lunar mountains are not only relatively but actually higher than those of the earth. Mt. Everest, the loftiest summit in the world, is but a little over 29,000 feet high, while some peaks on the moon reach the great height of 36,000 feet—nearly seven miles. There are over forty lunar mountains higher than the highest peak in the United States. This great height of the lunar mountains is but the natural result of the small value of gravitation at the surface of the moon. Owing to the small mass of the moon she attracts bodies at her surface only about one-sixth as strongly as does the earth. A body

which weighs six pounds on the earth's surface would weigh only one on the surface of our satellite. Volcanic forces which on the earth hurl rocks and lava one mile into the air would on the moon throw the material several times as high, and in falling such matter would be scattered over a vastly greater area than on the earth.

Irrespective of the craters, the entire surface of the moon is extremely rough and broken and is traversed by deep, narrow clefts and long light coloured rays. These bright streaks surround certain craters, radiating from them in all directions and extending for hundreds of miles. The beautiful crater Tycho is the centre of an immense system of rays, which pass across mountain and valley and cover a large portion of the visible surface. As a rule these rays are from five to ten miles wide, being narrow and brilliant near the crater, broad and faint at their extremities. They are neither much above nor below the general surface of the moon, do not cast shadows, and are never visible at lunar sunrise or sunset.

The great rays about Tycho become more and more conspicuous as the sun rises higher and higher and at the time of full moon, when the sun is directly overhead, they are the most striking feature upon the disc. At this time the light shines directly into the craters, the mountains cast no shadows, and craters and mountains become inconspicuous and lost in the general illumination. The rays stand out brilliantly and the moon looks like a great cracked globe.

Many and varied explanations have been suggested for these rays. By some they are thought to be great cracks in the lunar surface, caused by the bursting pressure from within; fissures filled with light coloured lava from below. Würdemann thinks of them as being caused by the splash of a meteorite striking a plastic surface; Pickering holds that the rays are streaks of snow lying in crevices. No satisfactory and universally accepted explanation has yet been given.

FIG. 4. PHOTOGRAPHS OF THE MOON TAKEN WITH THE 40-INCH YERKES TELESCOPE.

Pickering [1] claims that there is yet an appreciable amount of water vapour and carbonic acid gas on the moon; that our satellite is not the dead unchangeable waste that has been pictured. The interior is not yet absolutely cold and minute quantities of these heavy gases are given off by the various craters. Owing

The Moon, by Wm. H. Pickering.

to the low pressure of the lunar atmosphere, such water vapour would immediately be deposited on the surface in its solid form, as snow or hoar frost. Water in its liquid form cannot exist upon the moon. The carbonic acid on the contrary would exist in the daytime as a gas and at night as a solid. Some slight traces of such an atmosphere on the bright limb of the moon have been observed. Certain brilliant patches upon the surface have been observed to wax and wane with the decreasing and increasing power of the solar rays. Snow and ice, according to Pickering, are found not only in the crevices, but on the summits of some mountains and especially on the highlands surrounding the crater Tycho.

While it is certain that no conspicuous changes are taking place on the lunar surface, yet there are indications that minor alterations are in progress. A little crater, Linné, was observed nearly a century ago and was described by Beer and Maedler in 1837 as bright and deep. Later this crater was reported to have disappeared. It is now visible, but it does not agree in size or character with the early descriptions and drawings of Beer and Maedler. The reality of this change, however, has not been proved beyond question; the early maps were made with small telescopes and the form and shape of the lunar mountains appear to change with the changing conditions of light and shadow. The angle at which the sunlight falls upon the surface is continually changing and it is all but impossible to get the illumination

twice exactly alike. Yet, with the tremendous variations in temperature between the lunar day and night, it would not be surprising to find rocks crumbling, walls falling in, and craters filling up.

CHAPTER II

THE EARTH AS AN ASTRONOMICAL BODY

IN an elementary text-book, published not so many years ago, there is an imaginary conversation between two schoolboys of the time of Columbus; one boy is taught that the earth is round and that by sailing toward the west a ship would ultimately arrive at the East Indies; the other that the earth is a flat disc and that a ship sailing to the west would soon come to the edge and tumble off into space. This latter view is pictured as being the one generally held throughout Europe and the few persons who then dared to think the earth a globe are regarded as cranks and visionaries far in advance of their times. Columbus, himself, is shown as a crazy man, laughed at and derided on all sides for holding absurd ideas as to the shape and size of the earth. The general impression conveyed by this little book is that toward the end of the 15th century the earth was generally regarded as flat and that only a few thought that it might be spherical. This impression is utterly wrong; at the time of Columbus it was only the unlearned and the intentionally ignorant who could have held such ideas.

Any one who could read, and who made the slightest pretence at learning, could not have failed to know that the earth is a sphere. Ever since recorded history began, it has been known to all philosophers and astronomers that the heavenly bodies all are spherical. Aristotle, in the early ages of Greek supremacy, pointed out that the earth is spherical and used several of the very arguments that are found to-day in elementary geographies and text-books.

While thus from prehistoric times it was well known that the earth is a globe, the first successful attempt to measure its size was made in Egypt, by Eratosthenes, about the year 200 B.C. He noted that, in what we now call the month of June, when the sun reaches its greatest distance north of the equator, objects at Syene, in Upper Egypt, cast no shadow at noon. That is, at noon, the sun was directly overhead, or in the zenith. At the same time at Alexandria, which was situated almost due north of Syene, the sun was found to be $\frac{1}{50}$ of a complete circumference south of the zenith, and hence Eratosthenes inferred that the entire circumference of the earth is fifty times the distance between these two cities. He found the distance between them to be 5000 stadia and thus concluded the circumference of the earth to be 250,000 stadia, a number which he changed for convenience into 252,000 stadia, in order to simplify computations by making an even number of stadia (700) equal a degree of latitude.

This method of Eratosthenes was fundamentally

sound and is, in fact, the method which is in use to-day. His application of the method was crude and his results were inaccurate, but this was due to the lack of instruments of precision and of the means of accurately measuring distances and angles. Even to-day the resources of science are taxed in the various operations necessary to measure an "arc of the meridian"; operations which require the use of the most delicate instruments of astronomy and of surveying.

The problem consists essentially of two parts.

1. The measurement of an angle; the difference in latitude between two given places, and,

2. The measurement of a distance on the surface of the earth; the number of miles, feet, and inches between the two places.

Eratosthenes had only the crudest instruments. For measuring the difference of latitude he had merely the "gnomon," an upright post, which cast a longer or a shorter shadow as the sun changed its position in the heavens. For the measurement of distance he had no instruments, and used merely the travellers' estimate. The average day's march was so many stadia and Syene was so many days' journey from Alexandria. Unfortunately there were several different kinds of stadia in common use and in the mutilations through which Eratosthenes's work has passed it is now impossible to tell which kind he made use of. If he used the ordinary Olympic stadium, then his result is some 20% too great, but if a special

stadium, of which some records have been found, was used, then his result was only about 1% in error. In other words, it can be said with certainty that Eratosthenes knew the diameter of the earth with considerable accuracy, that his estimate made it greater than 8000 miles and less than 9500.

A little later Posidonius made measures similar to those of Eratosthenes and determined the earth to be 180,000 stadia in circumference; a result as much too low as the former was too high. This value was adopted by Ptolemy in the *Almagest,* which appeared about the year 150 A.D. and remained the standard text-book of astronomy for over thirteen centuries.

Not until the 15th and 16th centuries was this measurement improved. At this time there was a great revival of learning; the world awoke as from a long trance: new lands had been discovered, new fields for enterprise opened before all. So in the realms of science, new and undiscovered lands were coming into view, the spirit of science was revolutionised, and new instruments and new methods of observation were invented. The voyages of Columbus, Vasco da Gama, and others showed the necessity for new and more accurate measurements of the earth.

The first serious attempt to revise the old figures, which had survived for so many centuries, was that of John Fernal, who in 1528 made a determination which was less than 1% in error. Richard Norwood in 1636 measured the distance from London to York and obtained the length of a degree with an error of

less than one half a mile; or an error of less than 200 miles in the circumference of the earth. A little later, in 1671, Picard made some measurements near Paris, leading to a result only a few yards in error for the length of a degree. These two determinations of Norwood and Picard figured largely in Newton's discovery of the law of gravitation. When he first conceived the idea that the force which keeps the moon in her orbit is the same as that which causes bodies to fall upon the earth's surface he attempted to verify this by calculations, using for this purpose the figures of Norwood. His calculations did not square with his theories and he was so dissatisfied as to regard his hypothesis as substantially defective. He laid the theory aside for some seventeen years, until the more accurate measurements of Picard were brought to his attention. He at once revised his calculations and arrived at his brilliant conclusion, establishing the law of universal gravitation.

From the time of Eratosthenes the greatest difficulty in this problem has been the accurate measurement of the distance between the two stations selected as the ends of the arc. The surface of the earth is rough and is traversed by valleys, by hills, and by rivers. Over such an uneven surface determination in feet and inches of the distance apart of two marks, separated by even a few miles, becomes extremely laborious and consumes much time and patience; the actual physical measurement of great distances becomes impossible. In the geodetic work of to-day a

comparatively short *base line* is levelled and measured with all the accuracy possible, and the greater distances are determined from this by means of an elaborate survey and *triangulation*. For measuring the base line metal bars or rods are used. These are carefully compared in the laboratory with the standards and their lengths at a definite temperature determined. Unfortunately, when these rods are taken into the field for actual use they are exposed to constantly varying temperatures and they expand and contract in a very troublesome way. Various devices have been used to eliminate the errors thus introduced; the simplest and best being the Woodward "ice-bar apparatus" used by the Coast and Geodetic Survey. In this the metal measuring bar is supported in a trough and completely packed in ice, and thus maintained at the uniform temperature of 32° F. With such an apparatus a base line can be measured with an error of only a fortieth of an inch in a mile, or one part in two and a half million.

The Rotation of the Earth. The earliest writer who conceived the idea of a rotating earth seems to have been Philolaus, a Greek, living in the 5th century before the Christian era. This idea was purely philosophical and not based on any observed phenomena. He regarded the earth as well as the sun, moon, and planets as revolving about a great central fire, the earth turning about an axis as it revolved so that this central fire should ever remain concealed from the inhabitants. Thus the idea that the earth

might rotate is very old, but, while from this time on some of the ancient writers seem to have favourably considered it, yet no one thoroughly grasped the essential facts. This unsettled state of mind is shown by the care with which, some centuries later, Ptolemy discusses this point in the first chapter of the *Almagest*. He clearly saw that, if the alternation from day to night is caused by a rotation of the earth, then points on the equator must move with a speed of nearly one thousand miles an hour, a velocity exceeding more than tenfold that of the wind in the severest storm. A terrible gale would thus always blow from the east; birds in flight and objects thrown into the air would be left behind and carried with frightful rapidity toward the west. As these things do not happen, the earth, Ptolemy concludes, must be at rest.

By thus failing to grasp the fact that the atmosphere is part of the earth and partakes of its motions, Ptolemy lost the opportunity of placing astronomy on a secure and permanent foundation. In all other respects his work was so complete and his mathematics so exact, that his work remained the standard treatise for thirteen centuries. Although he started with a wrong foundation, yet he built up upon it a complete and satisfactory theory of the apparent motions of the heavens. He could have made a very fair almanac for the year 1907; he could have predicted the day on which each new moon will occur.

Not until the time of Copernicus, in 1543, was the

Ptolemaic theory of an immovable earth seriously attacked. Copernicus, in his great book, ***De Revolutionibus Orbium Celestium,*** showed clearly that the hypothesis of a rotating earth explained the phenomena of the rising and setting stars as satisfactorily and much more simply than the ideas of Ptolemy. All the phenomena then known could be fully accounted for upon either supposition: either that the stars are attached to a great celestial globe which turns around once each day, or that the earth itself rotates about an axis and the motion of the stars is only apparent, not real. Copernicus could not *prove* that the earth rotates—the instruments and methods of observation necessary for this were not then invented; he could only show that it was probable, and that the rotation of the earth offered the most sensible and satisfactory explanation of the apparent motions of the heavenly bodies.

From the time of Copernicus the rotation of the earth was an accepted fact of science, but it was not until 1851 that an actual, experimental proof could be shown. In this year Foucault devised and executed his brilliant pendulum experiment by which the rotation of the earth can actually be seen.

An ordinary pendulum is supported on knife edges or on pivots so that it can swing in only one plane. The pendulum of a clock swings back and forth always in the same plane; if set swinging from the front toward the back of the clock it would at once come to rest. Foucault devised a pendulum which is free to

swing in any direction. It consisted of a heavy iron ball supported by a thin flexible wire which was securely fastened at the upper end in such a manner that it would swing freely in any direction. This wire was some 200 feet long and was hung in the dome of the Pantheon in Paris. On the bottom of the ball which formed the bob of the pendulum was a sharp steel point and below the pendulum was a circular table about 12 feet in diameter. On the top of the table was strewn fine sand so that as the pendulum swung from side to side the point would leave a little mark on the surface of the sand. The pendulum was drawn to one side and held in place by a string and left for a number of hours until it became absolutely at rest. The string was then burned and the pendulum allowed to swing back and forth. By all these precautions the pendulum was started in motion in an absolutely true plane, the point drawing a straight line across the surface of the sand. On its backward swing, however, the point of the pendulum did not follow in this mark, and each succeeding swing of the pendulum showed the marks to be constantly changing. The plane in which the pendulum was swinging was apparently slowly deviating toward the right. This experiment was tried over and over again and always with the same result, the plane in which the pendulum swung appeared to shift toward the right and always it would deviate the same amount in the same length of time. Now there can be only one explanation of this, and that is, that the

floor of the Pantheon was really invisibly turning under the plane of the swinging pendulum. If a pendulum were supported directly over the north pole and set swinging in any one direction, then once in 24 hours the earth would rotate under the pendulum and the pendulum would draw on the surface of the earth at the pole a series of radiating lines.

When the pendulum is set in any other latitude than that of the north pole the effect will be similar but not identical. The surface of the earth will revolve under the pendulum and the point will trace out intersecting marks. In the northern hemisphere the pendulum would appear to deviate slowly toward the right; in the southern hemisphere toward the left; and the amount of deviation would depend upon the latitude of the place in which the pendulum is supported. The deviation becomes less and less as we approach the equator and finally at the equator vanishes. In New York city the deviation of such pendulum is about 10° per hour.

There are numerous other ways by means of which the rotation of the earth can be demonstrated. For example: if a number of bodies be dropped from a very great height there is found to be a tendency for them to fall to the eastward. Small and perfectly round balls have been dropped with great care into deep mines, and careful measurements show that they strike the bottom a small fraction of a foot to the eastward of the point vertically under the starting-point. The top of the mine is further from the centre

of the earth than the bottom and is therefore moving faster toward the east, and a body dropped from the upper part retains its eastward motion as it falls and strikes to the east when it reaches the bottom. Similarly a ball thrown from a moving train partakes of the motion of the train and reaches the ground many feet in advance of the object at which it is aimed. As a result of many trials with bodies having a free fall of 520 feet, an eastward deviation of 1.12 inches was observed. According to theory this deviation should have been a trifle less, or only 1.08 inches.

So far as can be determined from observation the rotation of the earth about its axis is perfectly uniform and the day is of the same length now as it was when the shepherds first watched the stars from the plains of Chaldea. From a comparison of the times at which eclipses, transits, and other astronomical phenomena occurred in by-gone years, it can be shown that the day has not changed by so much as the hundredth part of a second since the time of Ptolemy. Yet certain theoretical considerations show that the day must be gradually growing longer. The sun and moon generate tides in the oceans and these tides act as a friction-brake upon the earth and tend to retard its rotation. Meteors fall and are deposited upon the earth's surface. Century after century the earth is thus growing bigger and, as its mass increases, the velocity of its rotation must diminish. These forces, which tend to lengthen the day, are extremely slow in their action and are to a certain extent

counteracted by the gradual cooling of the earth and its consequent shrinkage. The movement of any mass toward or away from the axis will of necessity affect the rotation of the earth; the gradual wearing away of mountain ranges and the subsidence of continents, the smoothing out of the surface irregularities—all tend to accelerate the rotation. The effects of all these varying tendencies are extremely small and cannot be computed in even the roughest manner. On the whole, however, the probability is that the day is slowly lengthening and that in the centuies to come the earth will rotate much more slowly than it does at present.

The Shape of the Earth. In 1671–73, John Richer, at the suggestion of Picard, undertook a scientific expedition to Cayenne, in latitude 5° north. Here he swung a pendulum and reached the then curious result that a pendulum of given length beat more slowly at Cayenne than at Paris. Some years before, in 1656, Huyghens had revolutionised the art of measuring time by the invention of the pendulum clock, utilising in his invention the principle discovered by Galileo. Galileo, it will be remembered, by watching the swinging of a lamp in the cathedral of Pisa had discovered the fact that the time of oscillation of a pendulum is independent of the length of the swing. Any weight hung by a string and swung to and fro oscillates back and forth in a period of time which depends only upon the length of the string. A ball suspended on a string or wire, so that the

distance from the support to the centre of the ball is 39.1 inches will take exactly one second to complete a swing from right to left, or from left to right. If the supporting wire be shortened, the pendulum will oscillate more rapidly; if lengthened, more slowly. Of course, such a simple pendulum when set swinging will oscillate for a few moments only and will gradually come to rest.

The force that keeps the pendulum in motion is the force of gravitation, the force that causes all bodies to fall towards the earth. If the force be increased then the pendulum will swing faster; if the force be decreased, the pendulum will take a longer time to oscillate back and forth.

Richer's observation at Cayenne thus showed that the force of gravity at that point of the earth's surface differed from that at Paris. The strength of an attraction diminishes as the distance from it increases, so these observations of Richer indicated that the earth is not a true sphere, that Cayenne is further from the centre than is Paris. Newton, using these measures of Richer, showed that the departure of the earth from a strictly spherical form is due to the attraction for each other of the particles forming the earth, combined with the rotation of the earth on its axis. If in past ages the earth were a hot, plastic mass, and at rest, then as it cooled off and became solid it would have assumed a spherical form, and every part of its surface would have been equally distant from the centre. But if, instead of being at

rest, this hot, plastic globe were in rapid rotation, then Newton showed that, in cooling, it would take the form of an ellipsoid, it would be flattened at the poles and bulged out at the equator.

This effect of rotation in changing the shape of plastic bodies can readily be shown in simple experiments. A light metal ring is mounted on a vertical axis about which it can be rotated with great rapidity. When the ring is at rest it is circular in shape, but when it is rotated it becomes flattened along the axis, bulging out at what we may call the equator. The faster the ring is rotated the greater and greater becomes its departure from circular shape.

In order to determine the exact shape of the earth, extensive surveys have been carried on, both by means of the pendulum and by geodetic measures of arcs of the meridian. The pendulum shows the shape of the earth only; the geodetic measures show both the shape and the size of the earth. At the equator one degree of latitude measures 68.7 miles, along the Hudson River one degree measures 69.0 miles, while in the extreme northern parts of Europe a degree measures nearly 69.4 miles.

According to the determination of Colonel Clarke, the head of the English Ordnance Survey, the earth has the following dimensions:

Equatorial radius........	3963.296	miles
Polar radius.............	3949.790	"
Difference	13,506	miles

These figures represent the major and minor axes of that ellipsoid which most nearly fits the surface of the earth. Some measures indicate that the equator is not a perfect circle, and there are many places where local and continental irregularities cause the actual surface to depart greatly from the theoretical geoid. Such irregularities are considered as altitudes or depressions in the surface. Taken as a whole the earth is a remarkably smooth globe, and its departure from a spherical form very slight. If a true model of the earth two feet in diameter be made out of well seasoned wood or metal, so as to get a very smooth and polished surface, then the differences in length of the polar and equatorial diameters would be about $\frac{1}{12}$ of an inch, and all the variations in height in the United States, all the mountain ranges and valleys, would be represented by the variations in a layer of varnish $\frac{1}{100}$ of an inch thick which protects the surface.

At present the size of the earth is known with extreme accuracy; the dimensions of the Clarke spheroid, as above given, are probably not in error by more than 1000 feet. That is, the actual distance from New York to the Cape of Good Hope has been accurately determined to within 1000 feet.

During the last few years a most important discovery has been made. The latitude of a place is not constant; the distance from the equator to any other point on the earth's surface is changing from day to day and from year to year. This variation of lati-

tude was first definitely shown to exist by Chandler in 1891. It arises from the fact that the axis about which the earth rotates is not a fixed line; the north pole, or point where this axis cuts the surface, wanders around in an irregular curve, covering in its wanderings an area equal to nearly two city lots. As the equator is an imaginary circle everywhere 90° distant from the poles, it must oscillate back and forth over the surface, keeping pace with the movement of the pole, and thus changing the latitude of every spot on the earth's surface.

This variation of latitude is rather minute, the extreme shift being some 0″.6, which corresponds to an actual motion of 60 feet. That is, at one time every building in New York City is 60 feet nearer the equator than at other times. During the years 1893–1900 an extensive series of latitude observations was made at Columbia University. The latitude was the smallest on September 15, 1895, and greatest on August 22, 1897, the total variation between these extremes being 0″.696, or very nearly 70 feet.

This wandering of the pole is a natural and logical result of the rotation of the earth.

Mass and Density of the Earth. The problem of determining the interior constitution of the earth is much more difficult than that of finding its size and shape. Radically different ideas have been held by well-known scientists, and many startling theories have been put forth by the "cranks," the would-be scientists.

One of the most extraordinary of these crank ideas was that of a retired naval officer, Symmes, which appeared in pamphlet form in 1826. He considered the earth hollow and the inside habitable. At the north and south poles he imagined great holes, connecting the exterior with the interior surfaces, and thought that vessels could sail over the edge, pass through the hole and enter the interior portions, which were pictured as being of a mild and delightful climate. This fanciful and absurd notion crops up every once in a while, a crank book with the same general idea having been published within the year.

This idea of a hollow earth is readily disposed of to-day, for measures can now be made which show that the average density of the earth is $5\frac{1}{2}$ times that of water. On the other hand the surface density, that is, the average density of the soil and rocks which make up the known surface, is only three times that of water. Taken as a whole, therefore, the earth is much more dense than the surface rocks and mountains, and at the centre its density must be very high, equal at least to that of the heavier metals.

The density of a substance is the amount of matter contained in unit volume: the densities of two bodies of the same size, or volume, will be proportional to their respective masses. The determination of the density of a body of known volume is the equivalent of finding its mass; the density can be found from the mass, or the mass from the density. Newton showed that every body attracts every other body and that

the force of attraction between any two bodies is proportional to the product of their masses, and decreases as the square of their distance apart increases. The attraction of a sphere, either homogeneous or made up of homogeneous concentric layers, is the same as if

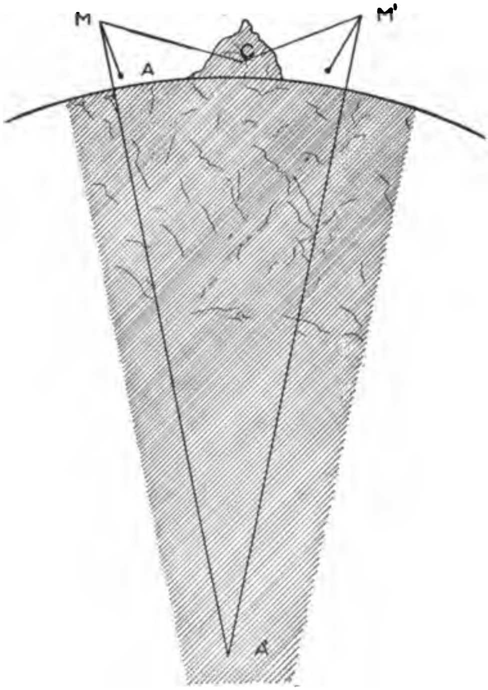


FIG. 5. WEIGHING THE EARTH.

all its matter were concentrated at its centre. The mass of a body is, therefore, measured by its attraction for and upon other bodies at known distances from its centre.

The method of determining the earth's mass or of

weighing the earth should now be clear. The attraction of the earth upon a body, *m*, at a known distance from its centre must be compared with the attraction exerted upon *m* by some other body of known mass and distance. The difficulty with the problem is not one of method, but of practice: the attraction of the earth is so incomparably greater than that of any body we can handle, that the actual experiments become exceedingly delicate and the measures difficult. The attraction of a globe of lead one foot in diameter for a particle close to its surface is less than one twenty millionth part that of the earth upon the same particle.

A very simple, but by no means the most accurate, way of weighing the earth is the so-called mountain method. At M, just north of a mountain, suppose a plumb-line to be hung. The bob will be attracted both by the earth and by the mountain; under the influence of the earth alone the plumb-line would take the direction of M A′; under the influence of the mountain alone, the bob would swing around until the line took the direction of M C; under the combined attraction of the two, earth and mountain, the line actually takes the direction of M A; very slightly different from M A′, as the attraction of the mountain is small compared with that of the earth. If the mountain be of fairly regular shape, the amount of matter it contains and the position of its centre of gravity can be determined by surveys and borings. Careful topographical surveys will show the shape

and size of the mountain, and by running tunnels and deep borings into it a good idea of its average density can be formed. The mass of the attracting mountain, and its distance from the plumb-bob, can thus be determined; the distance of the bob from the centre of the earth is known to be some 4000 miles.

If now the amount by which the pendulum is pulled out of its normal position by the attraction of the mountain be determined, then the ratio of the mass of the mountain to that of the earth can be found by the simplest computations. In order to find the disturbing effect of the mountain, the plumb-line is moved to M′ just south of the mountain. Here the bob will be attracted toward the north, toward the mountain. The latitude of M′ as determined from observations will, therefore, be too small, just as the latitude of M, on the north side of the mountain, will be too great. The difference between the latitudes of M and M′, as determined from observations, will, therefore, be greater than the actual or true difference, which can be found by measuring the distance on the surface of the earth between M and M′. And this difference between the results of observation and measurement is twice the deviation of the plumb-line by the attraction of the mountain.

In actual practice, of course, a plumb-line is not used. It is replaced by a dish of mercury, whose surface is perpendicular to the direction of gravity, and by means of which a telescope can be pointed with extreme accuracy toward the nadir.

This method was tried in Scotland nearly a century and a half ago by Maskelyne, who found the average density of the earth to be about 4.5. Later determinations show this figure to be much too small.

Another and far more accurate method by which the mass of the earth can be determined is by means of the apparatus first used by Lord Cavendish in 1798, and this method possesses the advantage that all the measurements can be carried on in a laboratory.

A large lead ball, a foot or more in diameter, is used instead of the mountain and its attraction upon a small metal ball is measured by means of a very delicate instrument, the torsion balance. The attraction of the earth for the same small ball is directly given by the weight of the ball itself. Comparing these two attractions and making allowance for the different distances of the attracting bodies from the small ball, the ratio of the mass of the earth to that of the large lead ball can be found, and thence the density of the earth. Cavendish found the mean density to be 5.5, that of water being taken as unity. Very recent experiments by Boys in England and Braun in Bohemia indicate that this figure is a little too low; the results of Boys give a mean density of 5.527.

This high average density gives some indication of the probable condition of the earth's interior. It is well known that the temperature increases toward the centre, the average rise being one degree Fahrenheit for each fifty feet in depth below the surface.

If this rate of increase be maintained, then one or two hundred miles below the surface the heat is sufficient to melt the rocks and fuse the metals that form the surface. This in connection with volcanic phenomena caused geologists to consider the interior of the earth as molten and the solid surface crust as comparatively thin. But the melting-point of rock-like substances is raised with pressure; and the pressure in the interior of the earth is enormous. A few yards below the surface this pressure is several times greater than the ordinary atmospheric pressure of the surface; at the depth of a few miles the pressure is measured by tons instead of by pounds. This increase of pressure is so rapid as compared to the increase of temperature, that at no point within the interior is the temperature high enough to melt the substances of which the earth is composed. Physicists and astronomers now believe that the earth is solid throughout, and that it is more rigid than steel. Volcanoes are mere pockets, mere local phenomena. The tides, the precession of the equinoxes, and the variation of latitude, all take place precisely as though the earth were a solid and extremely rigid body: these phenomena would be utterly changed were the earth a fluid mass, surrounded by a thin solid shell.

CHAPTER III

TIDES AND TIDAL EVOLUTION

THE tides are the regular periodic changes in the level of the sea caused by the attractions of the sun and moon. Twice in each twenty-four hours the water rises and covers rocks and shoals along the coast, and just as regularly twice each day the water sinks back, leaving the reefs and beaches again bare. In this periodic ebb and flow of the tide there are each day moments when the sea-level is highest and moments when it is lowest. These moments are the times of "high" and "low" water respectively and the positions of the sea-level at these instants mark the heights of the high and of the low water. This periodic rise and fall of the water is accompanied by strong currents, which sweep up and down the coast. In deep bays and narrow arms of the sea these tidal currents are often very powerful and become a menace to navigation. These currents are often loosely referred to as "tides."

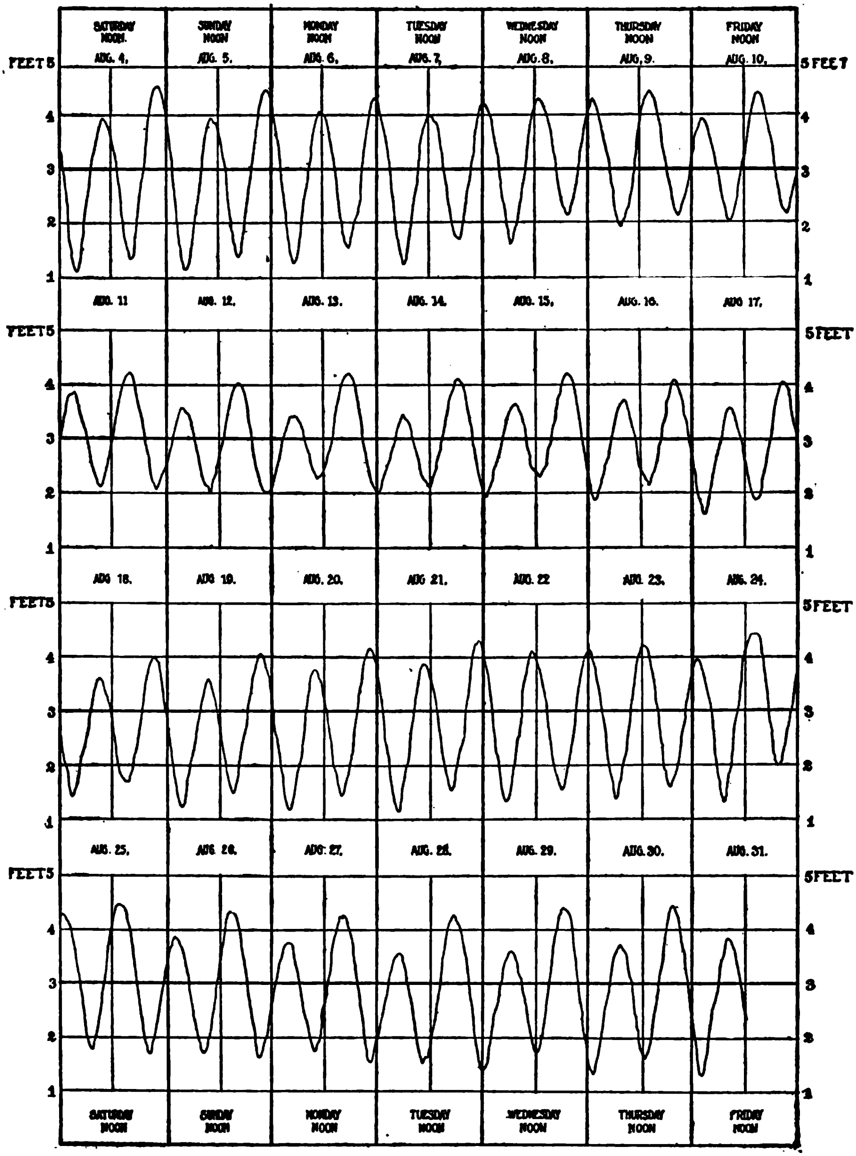
The average interval from one high water to the next is not exactly twelve hours, but more nearly twelve hours and twenty-five minutes, so that the time of the corresponding high water is apparently

delayed some fifty-one minutes each day. This average retardation of the tides is identical with that of the moon, the interval between two successive passages of the moon over the meridian being twenty-four hours and fifty-one minutes. The time of high water does not exactly coincide with the time of meridian passage of the moon, but follows after it by a certain number of hours and minutes; an interval which varies for each place of observation. Even for a single station, however, this difference of time between the moon's passage and high water is not absolutely constant, but fluctuates a few minutes either way during each month. The average interval, known as the "establishment of the port," can be determined from a few days' observations and furnishes a rough guide for predicting the time of high water. The establishment for New London is nine hours and twenty-six minutes; each day, therefore, the time of high water will be nine hours and twenty-six minutes later than the time given in the almanac for the moon's meridian passage.

Not only is the moon's agency shown in the daily retardation of the tides, but also in the monthly variation in their height. When the moon is nearest the earth the tides are nearly twenty per cent. higher than when she is farthest off. But the most noticeable variations in the height of the tides occur two or three days after new and full moon, when the rise from low to high water is greatest. These, the highest tides of the month, are called "spring" tides. The

smallest range between high and low water occurs near first and third quarters and the corresponding tides are called " neap " tides.

These characteristics of the tide, the daily retardation and the monthly variations in height, are beautifully shown in Figure 6. The curves there shown on a reduced scale were recorded during four weeks of August, 1906, on an automatic gauge at Shelter Island, New York. Such a tidal gauge consists of two essential parts, a float, which rises and falls with the water, and a recording apparatus. The surface of the water is constantly ruffled by waves, which keep an ordinary buoy or float in constant agitation and which completely mask the effect of the tide. In order to secure smooth water for the float, a well or tank is sunk near the beach line, and this well or tank is connected with deep water by a pipe of small diameter ending in a perforated rose or nozzle. The sea-water flows freely back and forth through this pipe-line, but the disturbing effect of the waves is effectually destroyed and the water in the tank is always at the same level as that of the open sea. In this tank is a metal can-shaped float or buoy, which rises and falls with the changes in sea-level. This float is suspended from a wire, which leads through a system of levers or wheels to the pencil of the recording device. This pencil rises and falls with the float, but for convenience its motion is reduced in some proportion; the pencil of the Shelter Island gauge moves, for example, one inch for every foot rise or



FIG, 6. SHELTER ISLAND TIDE CURVES FOR AUGUST, 1906.

fall of the float. The paper against which the pencil rests is drawn forward by clockwork so that a continuous curve is drawn. Thus is obtained a permanent record which shows the height of the sea at any moment of the day or night.

In the diagram the curve is broken up into four parts, each part representing the tidal record for one week, from noon on one Friday to noon of the next Friday. The curves for the corresponding days of the week are thus found in the same vertical line. The vertical heights give the level of the water at any instant on an arbitrary scale of feet; the horizontal scale shows the time, the hours of the day and night. The first striking peculiarity of these tidal curves is the great disparity between the heights of the two tides each day. In nearly every instance the afternoon or evening tide is from six inches to a foot higher than the morning tide. This is the diurnal irregularity, and this irregularity will be specifically discussed later. The daily retardation of the tide is also well exhibited. On August 4th it was high tide at 9.45 A.M.; on the 5th at 10.30; on the 6th at 11.15, and on the 7th at 12 o'clock noon. By the 18th the retardation amounted to nearly twelve hours, the times of high and low water being very nearly the same as on the 4th; but the high water, which occurred at 9.45 in the morning of the 4th, on the 18th came at 10 o'clock in the evening, a total retardation of twelve hours and fifteen minutes in fourteen days. This gives an average daily retardation of fifty-two (52)

minutes, agreeing very closely with the corresponding quantity for the moon. Thus, so far as the times of high and low water are concerned, the tides repeat themselves very closely every fortnight.

The character of the tides varies conspicuously during the month. On August 4th to 6th the range of the tide was the greatest; the largest variation in level between consecutive high and low waters being 3.5 feet between the afternoon tide of August 4th and the morning tide of the 5th. The smallest variation occurred in the morning tide of the 13th, when the difference between high and low water was only 1.1 feet, less than one-third that of the 4th. From this time on the range increased until the 21st, when it was a little more than three feet, and then it began again to diminish, reaching a minimum of 1.8 feet on the 29th. The moon was full on August 4th, new on the 19th, and the first and last quarters fell on the 26th and 11th August respectively. The relation between the spring and neap tides and the phases of the moon is thus clearly brought out. Still further the neap tides of August 12th and 13th were lower than those of the 28th and 29th, and the reason of this is clear, for the almanac shows that on August 12th the moon was at its greatest distance from the earth, whilst on August 26th she approached nearer our planet than at any other time during the month.

These curves thus clearly establish a connection between the moon and the tides. The height, or range, of the tides depends primarily upon the phase of the

moon and secondarily upon the distance of the moon from the earth. The highest tides of all occur when these two causes act together or when new or full moon happens when the moon is nearest the earth, or in perigee, as astronomers call it. The dependence of the tides upon the *phase* of the moon indicates the sun as one of the principal factors in causing tides. The sun generates tides exactly similar to those raised by the moon. Spring tides are caused by adding together the two smaller tides due to the moon and to the sun; the neap tides are caused by these two tides being opposed to one another, the moon causing a high tide at the moment the sun would cause a low tide.

The intimate connection between the tides and the moon has been recognised since the time of Posidonius, but not until the time of Newton was the reason for this connection known. In the *Principia* he showed that the tides are a direct and necessary consequence of the law of gravitation. Over a century later, in 1774, Laplace, the great French mathematician, found that Newton's simple methods would not adequately explain all the tidal phenomena and he developed the formulas and methods which became the real basis for all modern tidal investigations.

According to the Newtonian law the moon attracts each and every particle of matter in and around the earth, and the strength of this attraction varies inversely as the square of the particle's distance from the moon. Now all those particles which are united

in the solid or rigid portions of the earth form a great sphere, or globe, eight thousand miles in diameter. This globe is attracted toward the moon as a whole, the strength of the attraction depending upon the average distance of all the constituent particles, and this average distance is that of the centre of the earth. A particle on the surface of the earth directly under the moon will be attracted more strongly than is the earth as a whole, for it is nearer the moon than the average particle at the centre. The moon tends to draw such a surface particle away from the earth, but this lifting force is very small compared with the whole attraction of the earth, and the action of the moon simply lessens the weight of such a surface body to a very small extent.

The distance from the moon to the centre of the earth is very nearly sixty times the radius of the earth, and hence the attraction of the moon upon the earth will be proportional to $\frac{1}{60^2}$. The surface particle directly under the moon is one radius, or four thousand miles, nearer the moon than the earth's centre, and hence the attraction of the moon for it will be measured by $\frac{1}{59^2}$. The difference between these two quantities, or $\frac{1}{60^2}-\frac{1}{59^2}$, measures the lifting force of the moon for the particle in question. Reducing these fractions to decimals and taking the difference, the result is 0.000,009,496. Now at equal distances the pull of the moon is only one eightieth ($\frac{1}{80}$) that of the earth; therefore, in order to compare this lifting force of the moon with gravity the above decimal

must be multiplied by $\frac{1}{80}$. The result of this multiplication is 0.000,000,1187 or in vulgar fractions $\frac{1}{8,424,000}$. That is, a 4000-ton ocean steamer loses one pound of its weight when the moon is directly overhead. This effect of the moon is so minute that it cannot be directly detected by any measuring instrument, yet it is sufficient to cause the tides and all the kindred phenomena.

This disturbing action is not confined to particles

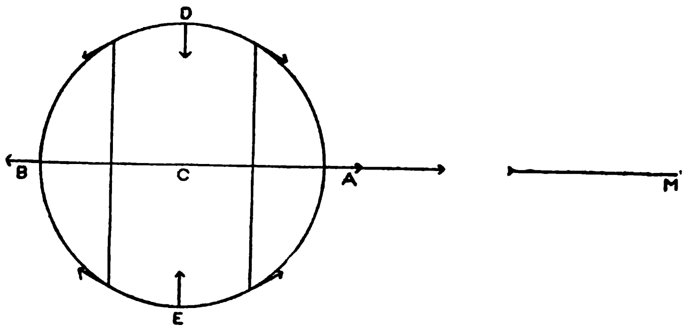


FIG. 7. TIDE-GENERATING FORCES.

at A, directly under the moon, but affects, to a greater or less degree, every portion of the earth's surface. At B, directly opposite the moon, there is a lifting force almost exactly equal to that at A. The attraction of the moon for the average particle of the earth at C is greater than that for a particle at B, for B is at a greater distance from the moon than is C. The moon tends to pull the earth as a whole away from the particle B, thus diminishing the force of gravity and causing a lifting force. At D and E,

and all points where the moon would be on the horizon, the effect of the attraction is to increase gravity, to pull bodies towards the centre of the earth. At D, a 4000-ton ship would gain about one half a pound in weight, or would weigh nearly a pound and a half more than when at A. At intermediate points on the surface the disturbing force is neither directly up nor down, but is partly vertical and partly horizontal. On two small circles, however, about half way between A and D, and D and B, respectively, the force is entirely horizontal and tends to move particles along the earth's surface.

The water of the oceans is mobile and moves along the surface under the action of these tide-generating forces. If the earth were surrounded by an ocean of uniform depth and both the earth and moon at rest, then the currents produced by these forces would flow until the ocean was distorted into an oval shape. The longer axis A B would be directed toward the moon and would exceed the shorter by about four feet. That is, when a state of equilibrium was reached and the currents ceased to flow, permanent tides would be formed and the difference between high and low water would be about two feet.

Further, suppose the earth to revolve upon its axis within this permanent shell of water. If there be no friction between the earth and water then the earth will revolve without disturbing in any way this distorted egg-shaped figure. An observer in any latitude would be carried around in a small circle once

in twenty-four hours and during this time would pass through regions of deep and of shallow water. Starting at F, such an hypothetical observer would be carried into gradually shoaling water, until at L the shallowest point is reached. It would then appear to be low tide. From this point, the rotation of the earth would carry the observer into deeper water until G is reached, after which the water would again appear to grow shallower. A second "low" would

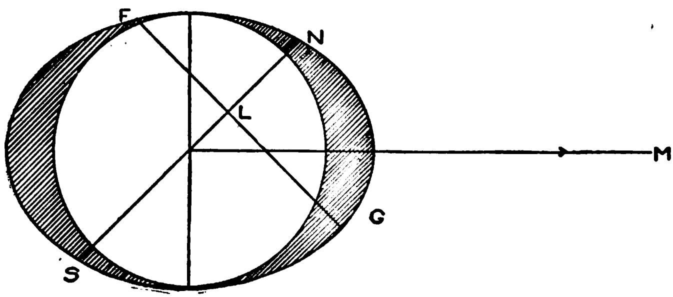


FIG. 8. THE DIURNAL VARIATION.

be reached directly opposite L, and a second "high" at the starting-point, F. Thus during the day there would be experienced two high waters and two low waters, and the high waters are very unequal, that at G being decidedly higher than that at F. This difference in height of the high waters is called the diurnal irregularity, and is clearly shown in the automatic records of Shelter Island. This inequality depends upon the latitude of the observer and upon the position of the moon. When the moon is on the equator, the ellipsoidal shell of water is symmetrically

placed with respect to the parallels of latitude and the two successive tides are exactly alike. The diurnal inequality vanishes in this case. This is shown in the Shelter Island tidal curves; the inequality disappeared on August 8th and 22nd, the days on which the moon's declination was zero. The inequality was a maximum on August 1st and 15th, the days on which the moon was farthest south and north, respectively, of the equator.

So far the moon alone has been considered. The sun, however, also acts on the ocean and produces similar, though somewhat smaller, tidal effects. The greater distance of the sun more than overbalances its greater mass, and its tide-generating force is only about two-fifths that of the moon. If, therefore, the sun acted alone it would produce an equilibrium tide of a little less than one foot. When the two bodies, the sun and moon, lie on the same or opposite sides of the earth, the two distortions will be superimposed and an equilibrium tide of nearly three feet produced. When the moon is in quadrature the major axis of the sun's distortion will coincide with the minor axis of the moon's, and the one will partially offset the other, producing a tide of about one foot only. Thus at new and full moon the two tides conspire and these large tides are the so-called "springs"; at first and last quarter the tidal range is only about one third that of the "springs," and these small tides are the so-called "neaps." The tidal curves in Figure 6 agree fairly well with this theory;

the spring and neap tides fall within a day or two of the changes of the moon and the spring range is a little over three times that of the neap.

While this equilibrium theory of the tides explains the general phenomena in a fairly satisfactory manner, it fails utterly to account for the time of day at which high and low waters occur. According to the diagrams the solar and lunar high tides are directly under the sun and moon, respectively. At the times of new and full moon these bodies are on the meridian together, and, therefore, the high spring tides should always occur at noon and midnight. It was full moon on August 4, 1906, and as a consequence the moon was on the meridian at midnight, yet on that day it was high water at Shelter Island at 9.45 in the morning and again at 10.15 in the evening. The high tide was apparently delayed some ten hours. Observations at various ports show that this departure from the theoretical time of high water is the rule, not the exception. And this departure takes all sorts of values, varying for the different ports without apparent rhyme or reason.

The explanation of this discordance is found in the varying speeds with which a wave traverses waters of different depths. If the ocean be suddenly disturbed by an earthquake or other momentary shock a great wave is created. When the shock is over, this wave spreads out and travels in all directions. Such a wave is a " free " wave, and if it be very long as compared to the depth of the water, it will travel at a speed de-

pending solely upon the depth. If the water be 200 feet deep, the wave will move at a rate of about 55 miles an hour; if the water be shallower the speed will be less; if deeper, greater. The ocean is some two or three miles deep, and the speed of a long free wave is from 400 to 500 miles an hour. If the ocean were 13¾ miles deep the wave would travel 1042 miles an hour, or complete a circuit around the earth's equator in exactly one day.

The tidal wave, however, in its inception is not a free wave. It is not created by a momentary earthquake shock, but by continuously acting forces. The tide-generating forces of the sun, for example, tend to make a wave on that portion of the earth directly beneath it, and as the earth rotates this point is carried around, making the circuit of the earth in twenty-four hours. At each moment the sun creates a new wave, the crest of each new wave being to the west of its immediate predecessor. Each wave as soon as created travels onward as a free wave at a speed depending only upon the depth of the water. The ocean is, as it were, disturbed by a great number of "free" waves, each starting from a different point and each moving on by itself. And at each point a new wave starts out every twelve hours, one when the sun is overhead and one when it is underfoot. Exactly how all these free waves merge and form one great tidal wave it is impossible to explain without the use of mathematics, but merge they do and order is produced out of chaos. The crest of the

resulting wave is not necessarily directly under the sun; in fact the trough of the wave may appear where the simple equilibrium theory would show the crest ought to be. The position of the crest, relative to the sun, depends upon the time required for a free wave to travel about the earth. If the ocean be of such a depth that a free wave circuits the earth in less than twenty-four hours, then the crest of the resultant wave would keep pace with the sun and the tide would be direct, or as indicated by the equilibrium theory. If on the other hand the free wave require more than a day to travel around the earth, then it can be shown that the crest of the tidal wave would be 90° from the sun. In this case it would be low water where the tidal forces tend to make it high water and the tide would be inverted.

Now the ocean is not more than three miles deep on the average, and the speed of a free wave cannot be greater than 500 miles an hour. Such a wave requires fifty hours to travel once around the equator, the sun requires but twenty-four. Hence, if the earth were covered by an ocean of this uniform depth, the tides at the equator would be inverted. Sixty-six degrees from the equator, however, the circumference of the circle of latitude is only 10,000 miles, and a free wave would travel once around this circle in twenty hours; while the sun requires twenty-four as before. For all points in this latitude, then, the tide would be direct, the high water keeping pace with the sun. Somewhere between the equator and this circle

of latitude there is a circle in which the waves are neutralised and the tide neither rises nor falls. What has been said of the sun applies equally well to the moon and thus the tidal waves created by these bodies are not the simple waves indicated by the equilibrium theory, but are extremely complicated. Near the equator it is low water under the moon, near the poles it is high water, and at some intermediate latitude the tidal effect vanishes.

In the actual case of the earth the tides are infinitely more complex than indicated by the above theory. The oceans are of various depths; the height and speed of the tidal waves, therefore, are radically different in different portions of the earth. Again, the continents divide the oceans and form great barriers which deflect and modify the tidal waves. In each ocean is produced its own individual tidal wave; in its origin a forced, in its subsequent travel a free, vibration. These waves, once formed, pass from ocean to ocean, around capes and promontories, modifying and changing the tides to the uttermost ends of the earth. The great tidal wave of the earth is formed, however, in the broad, deep waters of the Southern Pacific. This wave spreads east and west, around Cape Horn and past Cape of Good Hope, and sweeps northward up through the Atlantic. Here it is met and modified by the smaller Atlantic wave. The combined wave travels nearly 700 miles per hour and reaches New York some forty-one or forty-two hours after the parent wave was started in the

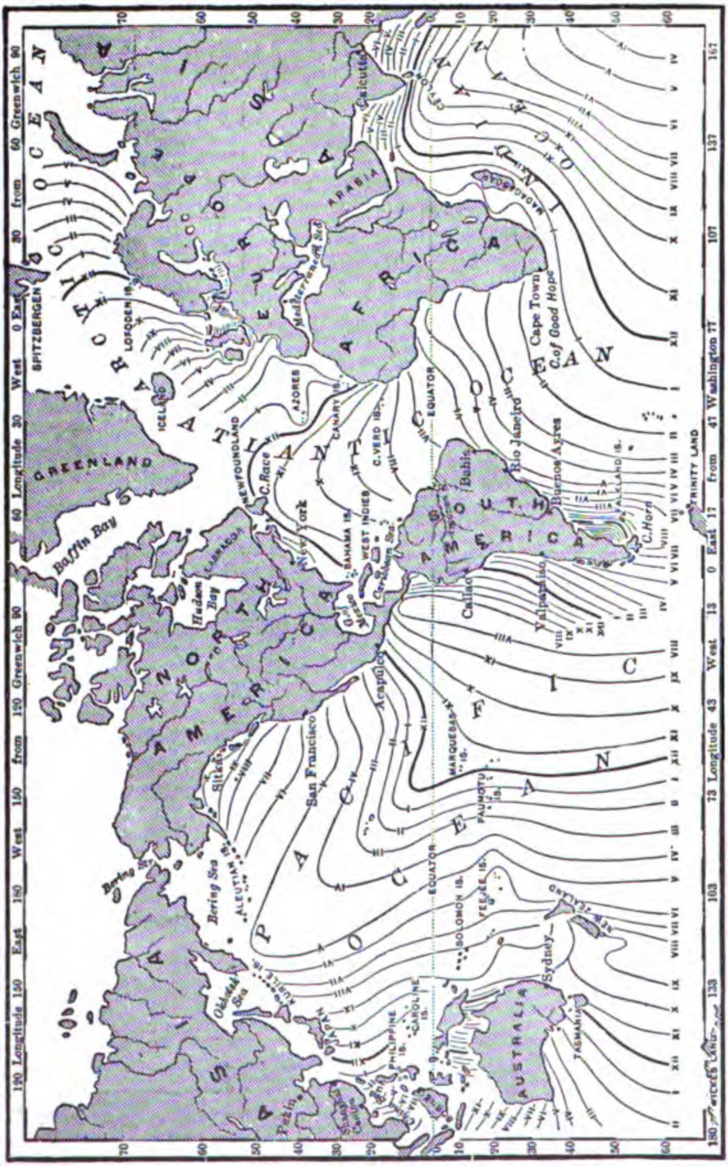


FIG. 9. MAP OF COTIDAL LINES.
From *General Astronomy*, by C. A. Young.

Southern Pacific. The tides along our coast to-day are mainly due to the action of the moon, yesterday and the day before, upon the waters of the Pacific and Indian oceans.

Two such great waves are started every day, the crests following one another over the same track, but each wave differs slightly from its predecessor. The varying positions of the sun and moon cause modifications and change the shape and height of the wave, producing the differences between spring and neap tides. As the parent wave is some sixty hours old when it reaches the German coast, there must be at least five or six simultaneous crests traversing the oceans.

As the tidal wave of the ocean approaches our shores, it is greatly modified. As it passes into shallower and shallower water the speed of the wave diminishes and its height increases. The contour of the land also has a marked effect. Where the shore is open and the bays broad and regular, the tidal wave varies little from that of the open sea. On the Long Island beaches and at New London the tides are regular and not more than two and a half to three feet in height. On the coast of Maine, on the other hand, the tides average ten and twelve feet, and in the Bay of Fundy tides of seventy to one hundred feet are not uncommon. From Cape Cod to Cape Sable the coast forms a great funnel, with mouth wide open to the sea and the Bay of Fundy forming the narrow spout. Into the broad entrance of this gulf the ocean tidal

wave sweeps. As the funnel becomes narrower and narrower the waters are crowded together and the wave becomes higher and higher, until at Horton Bluff it averages sixty feet in height.

On the east coast of England there are many peculiarities of the tide. The Atlantic tidal wave is divided, one part passing through the Channel and the Straits of Dover, the other around the northern end of Scotland and so into the North Sea. These two waves travel along the coast in different directions, one north, the other south. When the crest of one wave meets the crest of the other, tides of considerable height are found; when crest meets trough the waves neutralise and there is scarcely any tide at all.

Tidal Evolution. In the deep waters of the ocean the tidal wave moves onward without any great displacement of the water itself. The form moves like the wave in a stretched cord, but the particles of water which momentarily form the wave do not depart very far from their mean positions. In shallow waters this oscillatory motion is transformed and great masses of water are actually set into motion. On a small scale a similar phenomenon may be viewed any day at the seaside. The waves of the ocean, caused by wind and storm, come rolling in toward the beach. Just outside the line of breakers a boat will ride at ease, rising and falling on the waves, but remaining practically stationary. Let the boat come just within this line, however, and the rushing water will hurl it far upon the beach. So the great tide wave on ap-

proaching the shore is changed into a mass of rushing water, which flows in over shoals and rocks and is again dragged out to sea. Thus are produced the tidal currents which sweep up and down the coast. Through the Race and the eastern entrances into Long Island Sound pour great masses of water. Six hours later the current is reversed and the waters of the Sound rush out to sea.

Now the waters cannot flow backward and forward over the rough, uneven bottom without a good deal of friction. This friction means the transformation of energy into heat. And the energy thus dissipated is largely derived from the rotation of the earth. The tides act as a brake and tend to slow down the speed with which the earth rotates, or in other words, tend to make the day longer. In order that a brake pressing against the rim of a wheel may be effectual and bring the wheel to rest, it must be attached to some fixed support: the brake of a carriage is attached to the axle or to the body of the waggon itself. The tidal brake of the earth is attached to the slow-moving moon. But action and reaction are equal and opposite, and as the tides tend to diminish the speed of the earth's rotation, they must at the same time accelerate the motion of the moon in her orbit.

This action of the tides upon the earth and moon is illustrated in Figure 10, page 68. In a shallow, frictionless ocean the tides are inverted at the equator, the tidal protuberances being found at A and B. The friction between the waters and the

earth retards the tides and throws the protuberances backward to H and H′. The attraction of the moon upon the protuberance H tends to drag the protuberance backward and retard the rotation, that upon H′ tends to accelerate it. But as these protuberances are sensibly equal and H′ is farther from the moon than H, the retarding effect must be greater than the accelerating one, and the total effect of the couple is to retard the rotation of the earth. The primary effect of friction is thus to change the times of high and low

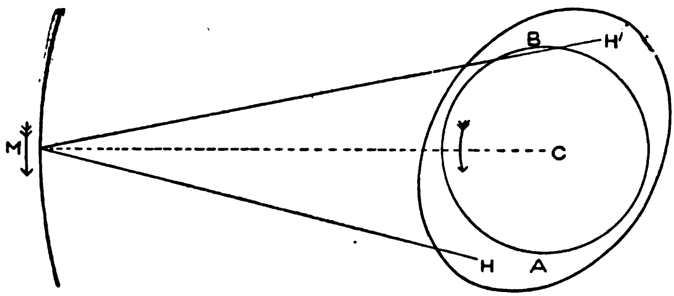


FIG. 10. TIDAL FRICTION.

water, and the secondary effect is to diminish the velocity of the earth's rotation.

The tidal protuberances in turn act upon the moon. The attraction of the spherical earth is directly toward the centre C, the attraction of the protuberance H is in the direction M H. This attraction can be resolved into two components, one in the direction M C, the other in the direction of the moon's motion. This latter component is extremely small, but it tends to accelerate the moon. In the same way H′

has a component tending to retard the moon. On account of the greater distance of H′ this retarding effect is less than the accelerating effect of H, and the total action of the tidal protuberances is to hurry the moon forward in its orbit.

It is a direct consequence of the law of gravitation that the size of a satellite's orbit about the primary depends solely upon its velocity at any point of the orbit. If the velocity be diminished, the orbit will be diminished, if the velocity be increased, the major axis of the orbit will be lengthened. But the larger the orbit, the longer the time the satellite will be in traversing that orbit. Tidal friction accelerates the motion of the moon and the effect of this acceleration is to increase the size of the moon's orbit, to push our satellite farther away, and, paradoxical as it may seem, to lengthen the month.

The friction between the water and the earth delays the time of high tide, retards the rotation of the earth, and lengthens the month. To-day this friction is very small and the consequent lengthening of the day and month very minute. During the last 2000 years the day has not changed in length by even $\frac{1}{100}$ of a second.

Upon these inevitable results of tidal friction George H. Darwin has built his theory of Tidal Evolution. The moon, according to this, was originally a part of the semi-solid or viscous earth; became separated from our planet; and in these long-past ages revolved close to the earth's surface. The mutual

attractions of the two bodies caused immense tides upon the surface of the planet and satellite, and the interaction of these tides gradually lengthened the day and drove the moon farther and farther away. Even the present relation between the moon and the earth, the length of the day and the month, is but a stage in the life history of the system. Darwin forsees a time, millions of years from now, when the evolution will be complete and the system reach a state of equilibrium. Then will the day and month be equal, the earth rotating upon its axis in fifty-five of our present days, and the moon will always be over the same portion of the earth's surface, the two bodies going round and round as though rigidly fastened to the ends of a bar.

Although tidal friction is to-day extremely minute and its action insensibly slow, yet in past ages it must have been considerable and its action comparatively rapid. Two causes contributed to this, the nearness of the moon to the earth, and the greater friction in the viscous materials of which the earth was composed. It can be shown that the retarding effect of the moon, acting through tidal protuberances of the same size, increases proportionally as the cube of the distance between the earth and moon decreases. If the distance of our satellite were halved without changing the tides, the retarding effect would be increased eightfold. But as the distance is diminished the tides themselves also become larger in the same cubic ratio, and the tidal retardation of the earth's

rotation must therefore be increased proportionally to the inverse sixth power of the distance. The ocean tides are now about two feet; but if the moon were brought to one half its present distance, the primary tidal wave would be sixteen feet high, and the tides in the Bay of Fundy would reach the enormous height of eight hundred feet. At this distance the retardation due to these immense tides would be sixty-four (64) times as great as it is at present. Were the distance of the moon reduced to one tenth of what it now is, tidal friction would be a million (10^6) times its present strength.

Again, in the early stages of its development, the earth was a semi-liquid, molten mass of rock. Any movement in this viscous substance would give rise to friction in comparison with which the friction of water passing over the ocean bottom is insignificant. Thus, while the action of tidal friction is immeasurably small to-day, it must have been a tremendous force in the days when the earth was molten and the moon close at hand. The lengthening of the day, insensible at present, must then have proceeded with great rapidity.

Darwin conceives the earth and moon as having originally formed a single semi-liquid viscous body. This planet rotated about its axis with great rapidity, its day being but one or two of our hours in length. Owing to this rapid rotation and its plastic condition the planet became excessively flattened, the equatorial diameter being several times greater than the polar.

If not disturbed by extraneous forces such a rotating liquid mass would have assumed one of several figures of equilibrium, as the pear-shaped figure of Poincaré for example. The exact figure assumed would depend upon the speed of rotation and the viscosity of the liquid mass. These equilibrium figures, however, for rapidly rotating liquid masses are unstable; slight disturbances or changes in the speed of rotation will cause complete change of figure and even possible breaking up of the mass into fragments. With alterations in the speed of rotation the pear-shaped figure of Poincaré changes; dimples form at the ends of the axis and then become deeper and deeper, until the figure gradually passes into the hour-glass form. And it is but a short step from this form to that of a planet and satellite, with their surfaces just touching and revolving as though rigidly fastened together.

However the separation may have been caused, whether by the rapid rotation of the original fluid mass or by the action of external forces, the moon just after her birth undoubtedly revolved so close to the earth as to nearly touch its surface. The length of the month and the day were almost identical, the moon continually facing the same side of the earth, and the two bodies revolved about each other like a single hour-glass-shaped body in from three to five hours. If the month and the day had been exactly equal the condition of the two bodies would have been one of unstable equilibrium. So long as there was not the slightest trace of a disturbance anywhere the

bodies would have gone on revolving in the same condition forever.

If the initial month were even infinitesimally longer than the day, the moon would slowly travel over every portion of the planet's surface and enormous tides would be developed. Tidal friction would begin to act, the day and the month would slowly lengthen, and the moon recede farther and farther from the earth. At first their changes would be extremely rapid, the month lengthening more quickly than the day, so that there would be first two, then three and four days in a month. Finally, after the lapse of many ages, the moon receded to her present position and the day and month became as we now know them.

This view of Darwin, that the moon was born of the earth, is now generally accepted, and the great influence of tidal friction in shaping and moulding the solar system recognised. Just as the moon raised great tides upon the earth, so, in the by-gone ages, the earth caused immense tides upon the then molten moon. The friction of these tides impeded her rotation and she gradually rotated more and more slowly, until she ceased to rotate relatively to the earth and her day became equal to her sidereal period. The moon has now solidified and the former tide has become a permanent distortion. The moon's equator is slightly elliptical and the longer axis of the ellipse is pointed toward the earth. To the action of tidal friction is due the fact that the moon always presents the same face toward the earth.

The sun causes tides of considerable importance upon the earth, and these tides must tend to retard the earth's rotation and lengthen the day. But the mass of the earth is extremely small as compared to that of the sun and the effect of the earth-sun tides upon the orbit of the earth is practically insensible. Tidal friction has not altered the distance between the sun and the earth to an appreciable extent, and the solar tides are probably as large to-day as they ever have been. When the earth was molten, however, the solar tides were more effective than at present in retarding the earth's rotation and they must have played a considerable part in the gradual lengthening of the day. At the present time the day is not lengthening by so much as one one-hundredth part of a second in a thousand years. But, if the oceans do not dry up myriads of years before the process can be completed, tidal friction will surely impede the rotation of the earth, lengthen the day, and ultimately cause the earth to always present the same face to the sun.

CHAPTER IV

THE DISTANCE OF THE SUN

OF all the heavenly bodies the most important to the inhabitants of the earth is the sun. The countless myriads of stars and the numerous planets could be blotted out of existence without sensibly affecting our daily life; the moon might be shattered into fragments and dispersed throughout space without materially changing the conditions under which we live and exist; the nights would be dark, the tides and currents which sweep our coasts would be radically modified, and the lengths of the day and the year might even be changed to an appreciable amount, but we could still go on living our lives, pursuing our business and our pleasures as we do to-day. But if the sun ceased to shine the days of the world would be numbered.

The sun is the centre from which is derived the heat, the energy, the life of the earth. In winter the sun does not rise so far nor remain so long above our horizon as in summer, and to the differing amounts of heat thus given us are ascribed our ever-varying seasons. The variations in climate, the difference between the torrid heat of the tropics and the rigours of

an arctic winter, are caused by the radically different amounts of solar heat received. A sensible increase or diminution of the solar radiation would modify the climate of the entire world. A radical decrease in the amount of heat received from the sun would cause the polar ice to spread toward the equator, would produce an age of ice and snow and bring death and destruction to the inhabitants of our world. The earth, undoubtedly, has internal heat of its own, but if the sun ceased to warm the atmosphere, for even a single month, the earth would grow cold and uninhabitable.

Energy derived from the sun warms and lights our houses, turns our mills, and drives our steamships across the ocean. Water plunging over the rocks at Niagara is intercepted and made to turn the giant turbines of electric power plants before it is allowed to hurry on its way to the sea. If the waters of the Great Lakes were not replenished Niagara would soon run dry and our mill-wheels stop. But year by year, and day by day, the sun's rays evaporate the waters of the ocean and lift them back again to the mountain tops, whence they flow downward into the lakes and rivers. Coal, the ordinary fuel of our daily lives, is transformed and fossilised plant life, and the force which builds up the plant cells and transforms the chemicals of the atmosphere and the earth into living tissue is the energy of the solar rays.

Our dependence upon the light- and life-giving properties of the sun has been dimly realised from the earliest times. In ancient Egypt the sun was

worshipped and became the god "Ra." The early Greeks personified the sun as a god, a charioteer, who drove his fiery steeds across the vault of the heavens, and none but Phœbus could safely guide the chariot in its daily course. In many lands and in many ages the sun has been worshipped as the all-powerful, the god of gods, and to-day the traces of this worship are found in all languages; attest the name of the first day of the week—Sunday.

The ancient astronomers were interested in and made careful studies of the motions of the sun; they had no methods of studying its physical characteristics, no means of finding out what the sun really is. From the earliest times the path of the sun through the heavens has been recognised and the length of the year known to within very narrow limits. In Homer there are frequent references to the year and to the month; in Hesiod is the earliest mention of the summer and winter solstices, as marking definite points of the sun's annual path. By the time of Herodotus the year was recognised as consisting of twelve months of thirty days each, or 360 days in all.

The first accurate measurement of the length of the year was made by Hipparchus about 130 years before the Christian era. He found the tropical year, the year upon which the seasons depend, consisted of 365 days, 5 hours, and 55 minutes, and this represents the length of time required for the sun to pass from the vernal equinox around the ecliptic and back again to the vernal equinox. The error in this determination

is only a little over six minutes, the true value being 365 days, 5 hours, 48 minutes, and 48.5 seconds. In arriving at the length of the year Hipparchus personally observed nine equinoxes, of which six were autumnal and three vernal, and compared these with several determinations made by Timocharis some 150 years previously.

Not only was the length of the year thus early determined, but approximations were made as to the size and distance of the sun. Aristarchus, some three centuries before Christ, measured the relative distances of the sun and moon and found the sun to be nineteen times farther from the earth than the moon, and consequently nineteen times as large as the moon. He knew with considerable accuracy the distance and size of the moon, and these measures showed the sun to be some six times larger than the earth and more than 1100 radii of the earth distant. Although it is now known that Aristarchus greatly underestimated both the distance and the size of the sun, yet his determinations remained unquestioned for more than fifteen centuries.

In the year 1543 Copernicus revised these ancient estimates and concluded that the sun is some 1500 radii of the earth distant. This is but little more than one twentieth of the actual distance, and only slightly better than the figure it replaced. Copernicus, however, revised the ancient system and gave to the world the true theory of the planetary motions. He showed clearly the possibility of explaining all

the varied loops and retrogressions in the path of a planet by supposing the sun to be the centre of motion and the earth, together with all the other planets, to revolve about it. But this idea of a central sun was not at once accepted; Tycho Brahe, the most skilful observer of his times, reverted to a modification of the ancient Ptolemaic system. The great stumbling-block in the way of the Copernican system was the annual parallax of the fixed stars; it was this that caused Tycho to take his backward step in the development of astronomical thought.

Copernicus clearly saw that if the earth is itself in motion, is travelling around the sun in an immense circle, then in winter the earth must be many millions of miles from where it is in summer. A star viewed from such widely separate points should appear to shift its position in the heavens, should appear to have a marked annual parallax. As no such shift had been observed, Copernicus rightly concluded that the stars are at a distance so immeasurably large that the path of the earth is but a point in comparison.

Nearly a century later Kepler tried to determine the distance of the sun from the earth by indirect means. From the laws of planetary motion, which he discovered, he was enabled to arrive at a correct representation of the solar system; he knew the correct shapes and the relative sizes of all the orbits, but did not know the actual dimensions in miles of any one orbit. He had, as it were, a correct map of the solar

system, but did not know the scale to which the map was drawn. As soon as any one distance on such a map became known the scale could be determined and all other distances found. Kepler attempted to find the distance of Mars from the earth. He failed because the instruments of that day were not sufficiently accurate. From this he concluded that the dimensions of the solar system are far larger than had been supposed and he increased Copernicus' estimate as to the distance of the sun, making that distance some 4500 radii of the earth, or some seventy-five times the distance of the moon.

It was not until the time of Cassini, in 1673, that a reasonably accurate determination of the solar distance was made. About this time, it will be remembered, Richer made some astronomical observations in Cayenne, among them some measurements of the position of Mars. Combining these with similar measures made in Paris the parallax of Mars was determined and thence the distance of the sun. This distance was found to be some 21,600 radii of the earth, or 360 times that of the moon: nearly twenty times the distance as first given by Aristarchus so many centuries before.

During the two centuries and more which have elapsed since Richer voyaged to Cayenne many improvements have been made in astronomical instruments and in methods of observation, and a corresponding advance has taken place in our knowledge of the size and distance of the sun. It is now known

that the sun is a great globe between 860,000 and 870,000 miles in diameter and nearly 93,000,000 miles distant. This distance is so great that the mind fails to grasp it unless some concrete illustration is used. In the Vanderbilt cup race the most powerful and fastest motor cars of the world covered the 300 miles of the course in five hours, averaging about sixty miles an hour. Now if the winner of the race travelled at that average speed day and night, without a stop, it would require some 175 years to pass over a distance equal to that of the sun from the earth. Again, to borrow an illustration from Professor Mendenhall, our nerves take an appreciable time to transmit sensation. If we burn our fingers, we are not instantly aware of it, for it requires a minute fraction of a second for the sensation of pain to travel along the nerves from the finger to the brain. Imagine, now, an infant with an arm long enough to reach out and touch the sun. Its hand would be burned off, but the child would die of old age long before it knew it was hurt, for 150 years would be required for the nerves to transmit the sensation.

The direct determination of this distance by the measurement of the sun's parallax is practically impossible. Many indirect methods have therefore been employed; the parallaxes of Mars and of the asteroids Victoria and Sappho have been used with great success by Sir David Gill; the aberration of light, the transits of Venus, and various minute irregularities in the motions of the moon and the planets have all

contributed to our knowledge of this fundamental unit of astronomy.

As Venus revolves about the sun in an orbit somewhat smaller than that of the earth and in a plane slightly inclined to that in which the earth moves, it will occasionally happen that the sun, Venus, and the earth will all be in a straight line and Venus will appear as a small black spot or disc passing across the face of the sun. These "transits" are rather rare phenomena, happening in pairs eight years apart, the pairs being separated by intervals of more than one hundred years. The last pair of transits were observed in 1874 and 1882; the next will occur in 2004 and 2012. At the moment when such a transit occurs Venus is only some 26,000,000 miles from the earth and her parallax is thus very much greater than that of the sun. Viewed by observers at various points of the earth she will appear on different parts of the sun's surface, and this apparent displacement is over two and a half times the parallax of the sun; that is, two observers at widely different stations on the earth might simultaneously see Venus projected on the disc of the sun at points one fiftieth of the sun's apparent diameter apart.

In 1679 Halley first recognised the importance of these "transits" and devised a method by which the parallax could be found from observations of their duration. At any station the apparent path of Venus across the sun's disc is a chord of the circle, and very slight displacements of the chord will make very

great changes in its length and in the corresponding duration of the transit. This effect is much more marked the farther the chords are from the centre. Hence if two observers measure accurately the respective lengths of time which it takes Venus to cross the disc, the positions of the chords can be located and their distance apart accurately determined. The absolute, or Greenwich, times of the beginning and ending of the transit are not required; the duration only is necessary, and it would seem that this could readily be determined, for clocks can easily be made which run with extreme accuracy for a few hours.

The transits of 1761 and 1769 were utilised and the parallax was found to be between 8″ and 9″. Again in 1874 and 1882 a concerted attempt on the part of many astronomers was made to solve the question of the solar parallax by means of transit observations. By this time accurate clocks and special instruments were available and other and more elaborate methods than that of Halley could be used. Unfortunately for the success of the method of Halley and of the somewhat similar one of Delisle, the times of beginning and ending of the transit cannot be determined within several seconds. The observations consist in noting the instant at which the edge of the planet is tangent internally to the disc of the sun. Instead of a round clear-cut black spot touching the edge of the sun, both the planet and sun are distorted and the so-called "black drop" appears. The two edges seem to cling together for a number of seconds, and

when they suddenly separate it is found that the planet is well within the disc of the sun and that the true time of contact has passed. This effect is due to the physical properties of light, to irradiation, and it cannot be overcome entirely in the best of instru-

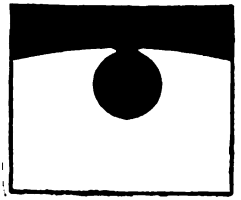


FIG. 11. THE BLACK DROP.

ments. Again, Venus is surrounded by a dense atmosphere and the light of the sun shines through this, causing the planet to appear surrounded by a bright or luminous ring and rendering the time of contact uncertain. In the transits of 1874 and 1882 specially trained observers with superb instruments could not determine the time of contact closer than five or six seconds; observers at the same station differing by these amounts.

Instead of determining the location of the chord by contact observation, it was possible, at the last transits, to make at frequent intervals a series of measures of the planet's position on the disc. From such series of measures made by different observers, the apparent displacement of Venus relative to the sun can be determined, and from such displacement the solar parallax can be found. These measures may

either be made with the heliometer, or determined from a series of photographs. The German astronomers placed greater reliance on the heliometer and made an immense series of measurements at many different stations. The American astronomers, on the other hand, used the photographic method, obtaining several thousand plates.

Unfortunately the results are not as satisfactory as could be wished. The instruments were necessarily exposed to the rays of the sun for some hours, and the heat seemed to distort the mirrors and throw the apparatus out of adjustment, so that consecutive photographs did not give concordant measures. Some idea of the delicacy of the measures and the difficulties connected therewith may be formed by noting that the sun's image, as obtained in the forty-foot horizontal telescopes of the American expeditions, was only four inches in diameter. On this picture the disc of Venus appeared projected as a round spot about $\frac{1}{8}$ of an inch in diameter. The measures consisted in locating the spot representing Venus with reference to the centre or edge of the sun. An error of $\frac{1}{10,000}$ of an inch would vitiate the result, for this minute quantity represents $\frac{1}{20}$ of a second of arc, a quantity greater than the whole uncertainty of the solar parallax.

Of all the geometrical methods for measuring the solar parallax, that used by Sir David Gill in his classic observations on Mars is undoubtedly the best. In this method all the observations are made at one

and the same station, by a single observer with one instrument. Thus are eliminated all the errors due to eccentricities of different instruments and the peculiarities of various observers. A glance at the accompanying diagram will make the essential points of this method perfectly clear. In the figure M is the planet, O the centre of the earth, and A, B, and C three positions of the observer, as he is carried

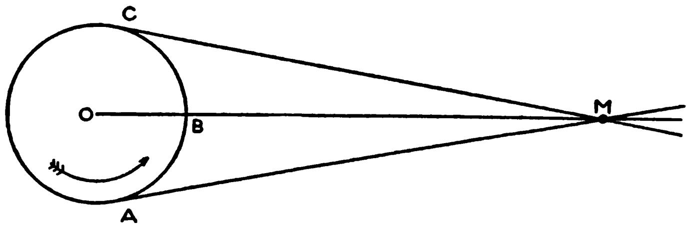


FIG. 12. GILL'S METHOD OF MEASURING THE PARALLAX OF MARS.

around by the daily rotation of the earth on its axis. When in the early evening the observer is at A, the planet is just rising above the eastern horizon and appears in the direction A M. A few hours later, when the planet is overhead, it appears in the direction B M, and finally before it passes below the western horizon it appears in the direction C M. The resulting apparent shift of the planet among the stars is shown in Figure 13, the upper circle representing the apparent position of the planet when rising, the lower when setting. By noting the time which elapses between the first and last observation, the distance which the observer has been carried by the rotation of the earth can readily be calculated, and this, together

with the measured shift of the planet, enables one to compute the parallax and thence the distance of Mars.

A station on or near the equator furnishes the best

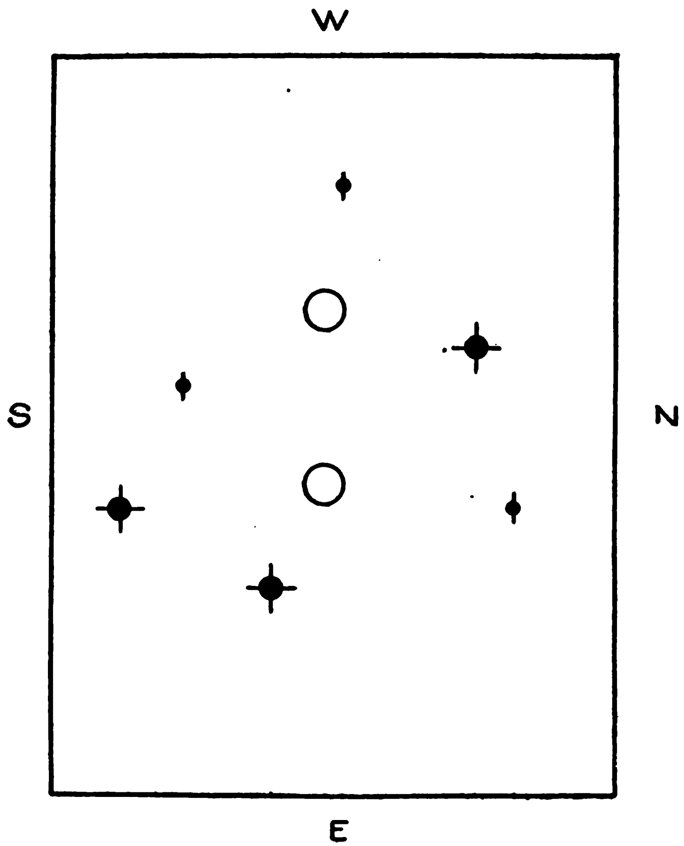


FIG. 13. PARALLACTIC DISPLACEMENT OF MARS.

results, for the daily path of the observer is here the longest. At the pole the observer would be station-

ary and the method inapplicable. For this reason Gill was sent in 1877 by the Royal Astronomical Society to Ascension, a small island in the Atlantic Ocean some 8° south of the equator. Here with a heliometer he made 350 sets of measurements. The comparison stars were first subjected to a system of triangulation, the relative position of each with reference to the surrounding ones being most carefully measured with the heliometer, and thus any errors in the positions of individual stars eliminated and the whole body of stars reduced to a consistent system. Each night, both at rising and at setting, the position of the planet was determined from two or more of these comparison stars. These measurements of Dr. Gill are probably the most precise of modern astronomy, the probable error in the determination of the planet's position on any single evening being only about one tenth of a second of arc.

During the few hours between the evening and morning observations the planet itself has moved among the stars. This motion has to be computed from the known orbit of the planet about the sun and allowed for in making the reductions for parallax. Now in discussing the results of his work Gill found a minute periodic difference between the observed and tabular right ascensions of Mars; this difference never amounted to more than 0″.376. In making use of these observations for another purpose, Newcomb found the cause of this periodic correction and showed that it was due to the omission of certain very small

nutation terms on the part of those who prepared the ephemeris of the planet. Thus the observations of Dr. Gill were so precise that they brought to light this curious error of computation, an error so involved and so minute that it could not have been detected by the very best meridian observations.

From these observations at Ascension the parallax was determined as $8''.783 \pm 0''.015$; a result extremely close to the truth. Similar methods have in recent years been used in connection with several of the planetoids. The principal advantage in using these asteroids lies in the fact that they show no appreciable disc and that, therefore, their positions among the stars can be more precisely determined than can those of Mars; but on the other hand their orbits are not so well known. Mars not only has a large disc, but is of a marked reddish colour and observations made on it are liable to errors peculiar to that planet.

In 1889 and 1890 systematic observations were made of the three planetoids Victoria, Iris, and Sappho; those of Victoria being carried out in the most thorough manner. These observations were discussed by Gill and Elkin and the following values of the parallax found:

From Victoria	$8''.800$
" Iris	$8''.825$
" Sappho	$8''.796$

Combining these separate results Newcomb deduced as the final result for this method the value,

$$8''.807 \pm 0''.006$$

In 1898 the little planet Eros was discovered and this body proves to be particularly well adapted for determining the solar parallax, as its orbit is such as to bring it at certain oppositions much closer to the earth than any other body of the solar system, the moon excepted. In 1900 the opposition was not the most favourable, yet many observations were made. In 1924 this body will be in a much more favourable position for these observations, as it will then approach the earth to within some fifteen million miles, more than twice as close as Mars ever does; and this opposition should, therefore, furnish an opportunity for a new and extremely accurate determination of the solar parallax.

The indirect methods of determining the sun's distance furnish more consistent and better results than do the direct geometrical methods heretofore discussed. Among these methods that depending upon the "constant of aberration" takes first rank, and the observations made at Pulkowa are generally admitted to furnish the best and most accurate value. The aberration here referred to is the apparent displacement of the stars due to the motion of the observer combined with the progressive transmission of light. The apparent direction of a star from the earth at a given instant is determined by the direction of the telescope through which it is observed, and this direction is not the same as it would be if the earth and the telescope were at rest. The telescope changes its position in space while the light from the star is travel-

ling the length of the tube, and, therefore, in order to see the star we must incline the telescope forward in the direction of the earth's motion. The angle through which the telescope must be so inclined is determined by the ratio of the speed with which light is transmitted through space to that with which the observer is moving. As the velocity of light is very great compared with that of the earth this angle is very small, being never more than 20″.5 and varying with the relative direction of the star. A moment's consideration will show that if the earth be moving directly toward a star, then no matter what the speed of the earth there would be no aberration, the apparent and true directions of the star being the same; whilst the greatest aberrational effect will be found in a star situated at right angles to the momentary motion of the earth. Now the "constant of aberration" is the maximum value of this angle, and is directly proportional to the velocity of the earth in its orbit divided by the velocity of light.

If now the constant of aberration be determined by astronomical observations and the velocity of light be found by physical experiments the above relation enables one to find the velocity of the earth in its orbit. But the velocity of the earth depends upon its distance from the sun, and as soon as the velocity in miles per second is known the distance can be computed and the parallax thus found. Many physical experiments have been made and the velocity of light in our atmosphere has been determined with great

precision. From such measurements made by Michelson and Newcomb the velocity of light *in vacuo* is found to be 299,860 kilometres, or 186,330 miles, per second, with a probable error of 30 kilometres.

Many determinations of the value of the constant of aberration have been made, among the best of which may be mentioned those of Peters, Gyldén, Struve, and Nyrén. The value as determined by the latter astronomer was $20''.492 \pm 0''.006$. Newcomb in his *Astronomical Constants* discussed all the available material and redetermined the value of the constant, taking account of the variation of latitude as found by Chandler. He found as a mean result from all the standard Pulkowa determinations $20''.493 \pm 0''.011$ and from all the other determinations the value $20''.463 \pm 0''.013$. The value adopted by the Paris conference in 1896 was $20''.47$, and this value is now used in the various government ephemerides and nautical almanacs. Combining this with the above-mentioned determination of the velocity of light the solar parallax is found to be

$$8''.8033$$

There are several important methods which depend upon certain periodic irregularities in the motions of the moon and the inner planets, resulting from the law of gravitation. Two of these deserve special mention, that depending upon the moon's parallactic irregularity, and that depending upon the earth's perturbations by Venus and Mars. These methods, however, involve complicated mathematical formulas,

without the use of which an explanation would be well-nigh useless. The especial advantage of these methods lies in the fact that they are cumulative—that, as the years go by and there are collected more and more observations of the planets, the determination of the constants of the solar system and the solar parallax becomes more and more precise. In 1874 Le Verrier, one of the greatest of French astronomers, would take no part in observing the transit of Venus, for he considered such methods of determining the parallax as crude and old-fashioned as compared with the elegant mathematical methods of gravitational astronomy.

In his *Astronomical Constants* Newcomb discusses at length the various modern determinations of the solar parallax and the errors to which each method is liable. After making liberal allowance for the probable sources of error, he rates the comparative values of the several methods and determinations in accordance with the weights assigned in the following table:

	π	Wt.
From Gill's Ascension observations.........	8″.780	1
From the Pulkowa constant of aberration....	8 .793	40
From contacts of Venus with sun's limb.....	8 .794	3
From observation of Victoria & Sappho.....	8 .799	5
From the parallactic inequality of the moon..	8 .794	10
From miscellaneous determinations of the constant of aberration......................	8 .806	10
From the lunar inequality in the motion of the earth	8 .818	1
From measures on Venus in transit.........	8 .857	1

From these Newcomb deduces as his final result for the parallax the value

$$8''.797 \pm 0''.0045.$$

The Paris conference adopted the value 8″.80, and this value is now used in all the astronomical ephemerides and nautical almanacs. Assuming the equatorial radius of the earth to be 3963.3 miles, as found by Clarke, then this parallax of the sun corresponds to a mean distance of 92,897,000 miles. A change of 0″.01 in the adopted value of the parallax would mean a corresponding change of 106,000 miles in the distance of the sun. And as the adopted value, 8″.80, can hardly be in error by this amount, we know with certainty the distance of the sun to within one hundred thousand miles, or twenty-five radii of the earth.

Size and Shape of the Sun. The apparent, or angular, diameter of the sun at distance unity is very close to 32′. While adjusting and determining the constants of the heliometers which were used in observing the transits of Venus in 1874 and 1882, the German observers made a great number of determinations of the sun's diameter, obtaining in all some 2692 separate measures. This great mass of data was most thoroughly discussed by Auwers, who reached the conclusion that the diameter of the sun is 1919″.26. A still later determination is that of Ambronn, who in 1905 published the results of a long series of heliometer measures made at Göttingen by Schur and himself. These observations extend over

a period of twelve years, from 1890 to 1902, and undoubtedly furnish the most accurate results yet obtained. The measures of Schur give 1920″.14, and those of Ambronn 1919″.80 as the apparent diameter of the sun, and these results may be accepted as very close to the truth.

Combining these measures with the distance of the sun as given in the last section, the actual diameter of the sun is found to be 864,750 miles, or nearly one hundred and nine times that of the earth. In the chapter on the earth that body was represented for illustration by an ordinary library globe, two feet in diameter: on this same scale the sun would be represented by a globe two hundred and eighteen (218.2) feet in diameter and distant about four and one-half (4.44) miles. The moon would be a little ball six and a half (6.5) inches in diameter and distant from the earth only one hundred and twenty (120) feet; that is, if the globe representing the sun be hollowed out, the system, earth and moon, could be placed within the hollow sun, the earth at the centre, and the moon in her orbit about the earth would never be but little more than half way out towards the sun's surface.

The great globe, the sun, is almost exactly spherical, the difference between the polar and equatorial diameters being so small as to be well-nigh impossible of accurate measurement. From his discussion of the heliometer measures, above mentioned, Auwers concluded that the polar diameter exceeds the equa-

torial by 0″.038, and he explains this apparent anomaly as being due to the tendency on the part of an observer to measure vertical diameters greater than horizontal ones. This evidence is quoted by Newcomb as conclusive that the sun is sensibly a sphere. Ambronn, as a result of his elaborate and thorough discussion of the Göttingen measures, reaches the same conclusion.

Certain evidence (from solar photographs and from the heliometer measures themselves) has been adduced by Poor, however, which seems to throw some doubt upon this conclusion. It is barely possible that the diameters of the sun are variable to a minute extent.

CHAPTER V

THE PHYSICAL CHARACTERISTICS OF THE SUN

THE study of solar physics began with the invention of the telescope. In 1610 when Galileo pointed his crude instrument toward the sun he found its surface covered with dark, irregular spots. The opinions concerning this discovery were many and varied, it being discussed from all points of view. The old ideas of the divineness and the perfectness of the heavens were revived in a new form; the sun could not be otherwise than perfect and these spots could not be due to actual specks and stains on the bright solar disc, but must be either optical illusions, or dark planets passing in front of its brilliant surface. Gradually, however, it was found that these spots really belonged to the hitherto immaculate sun. Galileo and his followers thought them to be clouds floating near the sun's surface and concealing the brightness below; others thought them to be the waste materials from the solar furnace, the burnt-out cinders of an immense fire. And just as a furnace fire burns more brightly after it has been raked, so these students of solar physics imagined the sun to blaze

forth with renewed brilliancy after this cindery refuse had been thrown off in the form of comets. Many years later, Lalande, the great French astronomer and mathematician, confidently upheld the opinion that these spots were caused by the uncovering of mountain peaks by the alternate ebbing and flowing of a great luminous ocean.

These dark spots, that mar the bright surface, were found to be in motion; when watched from day to day were found to travel slowly across the luminous disc. The early observers saw a spot appear on the eastern edge of the sun, move slowly toward the centre, cross the disc, and disappear at the western limb. Whether the spot passed through the centre, or along a shorter chord above or below the centre, the actual time of crossing the disc was always about the same number of days, and in this apparent motion of the spots Galileo recognised an actual rotation of the sun about an axis in a period of about one month.

The true form of these sun-spots was first clearly shown in 1774 by Wilson of Glasgow, when, by carefully noting the apparent changes in form which they assume as they cross the disc, he proved them to be vast excavations in the sun's substance. This fact, that the spots are hollows or pits in the sun, he clearly established, but unfortunately he tried to form a theory from this one fact alone and was led astray. He thought the sun might consist of two kinds of mat-

Plate III.

Calcium Flocculi Surrounding the Great Sun-spot of October, 1903, as Photographed at the Yerkes Observatory

ter, the greater part being a cool dark solid, the remainder a thin ocean of luminous fluid which completely enveloped the inner cool globe. Disturbances, or storms, caused holes in this solar ocean and through these openings the real body of the sun was occasionally seen. Starting with this idea, Herschel some twenty years later elaborated a theory of solar physics most remarkable for its fancifulness and ingenuity, but totally wrong and absurdly impossible. To him the sun appeared to be a large, eminent, and "lucid" planet; its true surface was cool and dark like that of the earth, diversified with hills and valleys and covered with rich vegetation and "most probably also inhabited, like the rest of the planets, by beings whose organs are adapted to the peculiar circumstances of that vast globe." This paradise was protected, according to this eminent astronomer, by heavy canopies of clouds from the intolerable glare and heat of the upper luminous region; while without the sun was a raging furnace, within there reigned a perpetual summer and a mild pleasant light.

Such a theory of the possible conditions prevailing on the sun needs only be stated to have its wild impossibility recognised. In utter physical absurdity it ranks with the speculations of the early poets and with the philosophers' stone of the Middle Ages. The interior of the sun must be at a temperature equal to, if not far hotter than, the exterior. The sun is known

to be radiating a vast amount of heat; is considered to be a great globe of intensely hot gaseous matter, the interior being under enormous pressure and the whole at a temperature so much above that of any furnace or electric arc that no real conception of it can be formed. Various attempts have been made to estimate this temperature and to express it in ordinary degrees of the Fahrenheit thermometer. These estimates vary widely; Secchi originally thought the temperature must be at least 18,000,000°; Pouillet and others have placed it as low as 3,000°. The first estimate is undoubtedly absurdly high, and the second is now recognised as being much too low. The most recent estimates place the effective temperature of the sun's radiating surface at about 10,000° Fahrenheit.

This vast globe of gases and vapours is radiating heat into space, is cooling off. The intensely heated particles of the interior rise to the surface, give off their heat, and sink back again, just as do the bubbles of steam in a kettle of boiling water. This circulation from within outward takes place over the whole of the sun and as a rule it proceeds steadily and quietly, without any marked disturbance. At times, however, this outward motion of the hotter particles takes the form of a sudden eruption. Somewhere near the scene of this eruption the photosphere settles down in consequence of the removal of the supporting matter, and the well or sink thus formed is filled by an inrush of the cooler materi-

als from above. The greater depth of the cooler vapours at this point causes the surface to appear comparatively dark and there thus appears a so-called sun-spot. But these spots are not really dark: they are relatively so only when compared with the surrounding brighter surface. The darkest part of the darkest spot, that part which appears intensely black in a drawing or in a photograph, is in reality more brilliant than the electric arc.

These spots appear sometimes singly, and sometimes in groups. In a typical spot the central portion is very dark, even black as compared with the surrounding surface, and is called the umbra. Around this is a lighter, irregularly shaded fringe, called the penumbra. The separation between umbra and penumbra is sharp and clear; there is no gradual fading and shading of one portion into the other, and the line of demarkation between the outermost edges of the penumbra and the sun's surface is just as well defined. The characters of the surfaces seem radically different; the umbra appears smooth and velvety, the penumbra shows numerous filaments and shadings. The appearance suggests a hole or excavations, the umbra being the bottom and the penumbra the sloping sides; or, as Young expresses it. the penumbra filaments partly shade the umbra from view "like bushes at the mouth of a cavern." The inner edge of the penumbra appears brighter than the outer edge, but this effect may be partially due to contrast, the inner edge appearing against the darker

umbra, while the outer edge is compared with the brilliant surface of the sun. Many spots are very irregular in shape, and often the penumbras of several spots coalesce, the umbras appearing in one immense irregular penumbra. At times, brilliant bridges appear, stretching from the outside brilliant surface, across the penumbra and extending into, or over, the darkest portions of the umbra.

These phenomena are very transient, spots and groups of spots appearing and disappearing sometimes with great rapidity. The average duration of a spot is, however, two or three months; that is, it may be seen and recognised during two or three transits across the sun's disc. Spots have been known, however, to last as long as eighteen months. In the growth and development of a spot, the umbra usually becomes fully developed before the penumbra appears, the spot attaining its full development very rapidly. After remaining quiescent for a longer or shorter interval the spot breaks up into fragments and these fragments separate and become minute spots. The final extinction of a spot is usually rapid, or, as Secchi expresses it, the surrounding matter seems "to fall pell-mell into the cavity" completely filling it. Occasionally the penumbra of a spot shows distinct signs of circular, or cyclonic, motion. The filaments show the characteristic spiral of the cyclone, and the whole spot turns slowly around. This rotary motion is the exception, however, rather than the rule.

In size these sun-spots are very large as compared with the dimensions of any terrestrial objects. The very small spots range from 500 to 1000 miles in diameter; not unfrequently a spot measures 20,000 miles in diameter and covers an area many times greater than the entire surface of the earth. The largest spot yet photographed at the Royal Observatory, Greenwich, was visible during January, February, and March, 1905. It was first seen on January 7th, and was observed during three rotations of the sun. It reached its greatest development during the second period of visibility, and on March 2 covered 3339 millionths of the sun's visible hemisphere; that is, its area was nearly forty (40) times that of the entire surface of the earth. At this time the umbra was small in comparison to the whole spot, covering about one sixth of the total area. The umbra was crossed by several bright bridges and numerous small secondary umbras were scattered throughout the spot. The rotation of the sun carried the spot out of sight on Febuary 11th, and it was not seen again until it appeared at the east limb on February 25th. By this time it was broken up into a long narrow group or stream. The principal spot was now quite irregular, was preceded by a number of small faint spots, and was followed by two or three round well-defined ones.

These spots are surface phenomena and are confined to certain well-determined zones of the sun's surface. That they are cavities has been quite con-

clusively proved, but whether the floor of the cavity is depressed below the average level of the solar surface is an open question. Certain observations seem to show that in the neighbourhood of a spot the whole surface is raised and the spot is a depression in this elevated portion, like a crater on the top of a low gradually sloping mountain. However this may be, the depth at which the umbra is depressed below the immediate surroundings is usually not more than 1000 miles, and it seldom or never exceeds 3000 miles. In relative thickness this layer of the sun, which can be examined and studied, may be compared to that of the velvety down on the surface of a ripe peach. The greatest number of spots is found in latitudes 10° to 20° north or south; a few are found nearer the equator than 5°; practically none have ever been observed beyond 45° of latitude, either north or south. Thus the spots are limited to comparatively narrow belts on each side of the equator.

Yet one more fact regarding the sun-spots is very important: they are periodic. Early observers had noted that the number of spots on the visible surface of the sun varied. But in 1851 Schwabe showed that the number of spots followed a regular law of increase and diminution, with a period of about ten or eleven years. This periodicity has been firmly established by later observations, and by a dicussion of all available data from the time Galileo first saw the sunspots in 1610. During a minimum practically no spots are visible, days and weeks often passing with-

out a single spot marring the brilliant solar surface. On the other hand, at times of maximum the certain portions of the surface are constantly covered with large and small spots, hardly a day passing without several being visible. The last observed minimum was in 1901, when the solar activity was less than in any year since 1878. On 297 days during the year the sun's disc was perfectly free from spots, and the spots and groups which were seen during the remaining 68 days were mostly small and insignificant. From July 25th to October 6th, a period of 74 consecutive days, not a spot appeared. The mean daily spotted area was not more than twenty-four (24) millionths of the sun's visible hemisphere. From this time on the solar activity grew in intensity, the percentage of days without spots falling from the 81 per cent. of 1901 to 72 per cent. in 1902, and to 20 per cent. in 1903. In this latter year only 72 days were free from spots, while on 293 days the sun's surface was spotted; thus 1903 almost exactly reversed the record of 1901. Still further, the early part of the year was comparatively free from spots, while from October 1st to December 24th there was a period of unbroken activity. During the next year, 1904, there was a slow steady increase in the number and size of spots; there were no days on which the sun was free from spots and the mean daily spotted area was about 470 millionths of the visible hemisphere, or some twenty (20) times that of 1901, the minimum year. In 1905, enormous groups appeared. Several of the single spots were

so large as to be easily visible to the naked eye. The great spot of February has already been mentioned; other great spots appeared during the summer months, and still others in October and November. In this latter month the groups were so large and numerous that they formed two great belts across the sun, one on each side of the equator. The mean daily total spotted area was about 900 millionths of the visible hemisphere. The maximum was reached in 1906, after which the solar activity declined and the fall toward a minimum is now (1907) well under way.

There have been many attempts to explain this periodicity. The average length of the sun-spot cycle is according to the latest researches 11.1 years. The period of Jupiter in its orbit is 11.86 years. These two periods are, therefore, somewhat alike and serious efforts have been made to show some connection between the two. The general idea in all these theories is that the attraction of the planet causes a "tide" on the solar surface somewhat similar to the ocean tides of the earth. The size of these solar tides varies with the position of the planet in its orbit and they are, therefore, periodic. While these tides are not large enough to be the direct cause of the sun-spots, it is supposed that in some way they release the activities of the sun, like a fall of a gun-hammer, which releases the stored-up energy in a charge of powder. The most elaborate of these attempts to find a gravitational cause for the sun-spot cycle was that of E. W. Brown, only recently published. He

included the action due to Saturn and found the combined tidal effect of Jupiter and Saturn, with minor modifications due to the inner planets. The curve representing the resultant of these tidal effects somewhat resembles the curve of sun-spot frequency. In the main the dates of maxima and minima in the two curves coincide, but not in all cases. In several instances periods of great solar activity were found where Brown's theoretical curve indicates a minimum.

On the whole these efforts to show a connection between the solar activity and the positions of the planets have failed. The tidal effect of Jupiter upon the sun is practically insignificant, being less than one five-hundredth of that of the sun upon the earth. That is, if the sun were a solid body like the earth and surrounded by an ocean, the tide produced by Jupiter in that ocean would be less than one twentieth ($\frac{1}{20}$) of an inch. It would seem incredible that minute variations in a tide of this size could in any way affect or cause such tremendous phenomena as the sun-spots.

The cause of the sun-spot period should undoubtedly be looked for in the sun itself. It is probably a natural period, due to the physical condition of the sun, as a rotating, cooling mass of gas, and possibly connected with the general circulation of, or convection currents in, the outer atmosphere of the sun. "Old Faithful," a geyser in Yellowstone Park, day after day, winter and summer, throws a stream of boiling water some two hundred feet into the air at regular intervals of sixty-five minutes. This

periodic activity is explained by the presence of peculiarly-shaped caverns and ravines in the rock formation and the action of internal volcanic heat. No one has ever thought of connecting this period with the varying positions of the moon, or planets.

Instead of the planets causing the sun-spots, these spots have a direct influence upon the nearer planets. It has been clearly demonstrated that the spots have a direct connection with various magnetic and electric phenomena on the earth. When spots are numerous on the sun, magnetic disturbances and auroras are numerous on the earth; when spots are scarce, auroras are few and the earth's magnetism quiescent. Remarkable coincidences have been observed; violent storms have been seen in sun-spots, and at the same instant magnetic instruments have recorded marked disturbances. In the accompanying figure the upper curve is the sun-spot curve, and shows the proportionate area of the visible hemisphere covered by spots. The lower curve shows the diurnal range of the magnetic needle. The correspondence between these two curves is so marked that it is impossible to doubt a connection between the two phenomena represented. The fact of this connection is known, but the nature of and reason for the connection have not been explained.

The sun-spots may have some effect upon the meteorology of the earth, upon the weather; but, if such an effect exists, it has not yet been demonstrated beyond all doubt. Many years ago Gould claimed

that the records made in the Argentine Republic showed a connection between the wind currents and the sun-spot frequency. Bigelow,[1] of the Weather Bureau, has investigated this subject in a most careful and painstaking manner and has reached the conclusion that such a connection does exist, that the average temperature and rainfall depend upon the relative frequency and size of the sun-spots.

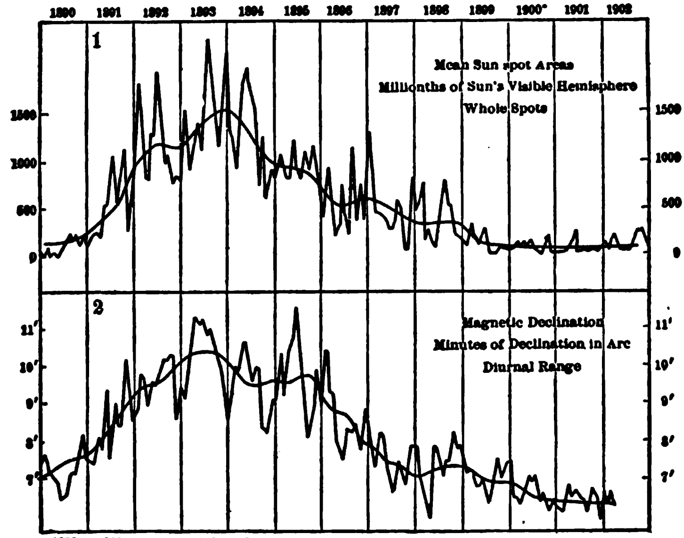


FIG. 14, SOLAR ACTIVITY AND TERRESTRIAL MAGNETISM.

About the middle of the last century Carrington deduced, from a long series of sun-spot observations, the fact that the sun does not rotate as a whole. Spots near the equator complete an entire revolution

[1] *Monthly Weather Review,* 1903, 1904.

in a much shorter period of time than do spots in high latitudes. This equatorial acceleration is somewhat more than two and a half days; a spot on the equator requiring not quite twenty-five days to complete a single circuit, while a spot in latitude 45° requires twenty-seven and one-half days. The earth's equator passes through South America a few miles to the north of the city of Quito, and New York city is in latitude 42°. If now the earth rotated as does the sun, then a day in Quito would be twenty-four and a day in New York twenty-seven hours long. Quito and the northern portions of South America, which are now directly south of New York, would each day slip along the earth's surface towards the east. After the lapse of a few days South America would displace Africa, and Borneo and Sumatra would lie directly south of New York. Again before a week had passed equatorial Africa would be found where now is South America. Such a rotation as this is an utter impossibility for a rigid, solid body, and the fact that the sun rotates in this peculiar manner is proof sufficient that it must be gaseous or liquid; that portion which is visible certainly cannot be solid.

This peculiar surface movement has been confirmed by many observations upon sun-spots and faculæ. The spectroscope has been utilised and Dunér has shown that the layer of the sun in which the Fraunhofer lines originate participates in this movement. His observations extend from the equator to within 15° of the poles, at which point the rotation period

was found to be 36.5 days. For the equatorial period he found 25.5 days, about half a day longer than the best determinations from spot observations. Thus different portions of the sun's surface rotate at different speeds; but this is not all: certain observations seem to indicate the existence of regular currents to and from the equator. The real motions of the various parts of the solar surface are extremely complicated. Perhaps this surface drift might be likened in a limited sense to the circulation of, and convection currents in, the earth's atmosphere. The heated air at the earth's equator rises and in the upper strata flows north and south toward the poles. Arriving at the cooler regions, this air is cooled, falls, and near the surface flows back toward the equator, displacing the heated air in the torrid regions. This circulation combined with the rotation of the earth gives rise to the "trade winds" and the equatorial calms. The phenomena of the solar drift, the sun-spots and their periodicity, are all probably connected with the cooling and circulation in the outer strata of the sun.

These problems are problems of physics, of the mechanics of a cooling mass of gas. Mathematical investigations point toward an ultimate solution along these lines. The cause of the sun-spot period will undoubtedly be found in the physical conditions of the sun itself and not in the action of any extraneous bodies.

When the visible surface, or *photosphere,* of the sun is more closely examined with the telescope it is

found to be unevenly luminous; there appear to be bright flakes scattered over a darker surface. These bright patches are five or six hundred miles long and are variously shaped; near a sun-spot they are drawn out and are much longer than they are wide. Nasmyth called them "willow leaves," others "rice grains," or "dots," and Langley likened their appearance to "snowflakes on a grey cloth." These bright flakes, or faculæ as they are now called, are scattered irregularly over the entire surface, being especially abundant in the vicinity of spots, and it has been calculated that if the entire surface of the sun were as brilliant as these faculæ then the brilliancy of that orb would be increased tenfold. These faculæ are elevated above the darker portion of the surface; often they appear as projecting beyond the edge of the solar disc. Until recently they were thought to be the upper termination of up-rushing currents, while the darker "pores" were thought to mark the positions of the cooler descending currents.

Closely connected, if not identical, with these faculæ are the prominences. They were first noticed and studied during the brief moments of a total solar eclipse. When the moon cuts off the last ray of direct sunlight, then instantaneously appears around the black disc of our satellite a brilliant, white, flickering halo. Many ancient records of this "corona" are to be found, but the importance of its careful study was not recognised until 1842. The eclipse of that year was total over the southern part of Europe and

all the noted astronomers hastened to the favoured region. Their expectations were far outdone by the wonderful spectacle disclosed; not only did the mysterious corona blaze forth with all its brilliancy, but close to the edge of the moon appeared three large prominences of a bright red or purple colour. These cloud-like pillars of flame were at least 50,000 miles high and they were described by Arago as "mountains on the point of crumbling into ruins." Great crowds of people were gathered about the astronomers and when the brilliant spectacle burst into view they raised the cry "Long live the astronomers!" To none, however, was the appearance of these red flames more of a surprise than to the astronomers themselves. For nearly thirty years thereafter the prominences could only be seen during the short moments of a solar eclipse. In 1868 Janssen and Lockyer, independently, discovered the spectroscopic method of studying these phenomena and opened a new and most fruitful field of solar research.

If it were not for the earth's atmosphere the prominences and corona could be seen at all times. The atmosphere reflects and scatters the direct light of the sun in all directions, and this reflected light is more intense than the direct light from the prominences. The direct light from the sun can be screened off, but this reflected light cannot be cut out by any ordinary mechanical means. If, however, a spectroscope be pointed at a prominence on the edge of

the sun, the slit will cut off all the direct light from the brilliant solar surface and the instrument will give two superimposed spectra; one that of the prominence, the other that of sunlight reflected from the atmosphere. The first of these consists of three bright images of the prominence, for a prominence gives out light of three definite wave-lengths only, the second of a long band of coloured light broken by dark lines. By an increase in the number of prisms in the spectroscope the second spectrum, that of the atmosphere, is spread out into a longer and longer band of light, each portion of which becomes fainter and fainter as the power of the instrument increases. On the other hand this increase has no effect upon the brightness of the first spectrum; the thin bright images of the prominence remain of the same size and brightness as at first; they are merely pushed farther apart. Thus the illumination of the background against which the prominence appears can be diminished until the prominence comes into distinct view, any one of the three images being used. This visual method of Janssen and Lockyer has been greatly improved by the application of photography. As early as 1870 Young succeeded in obtaining with the old wet-plate process a successful photograph of a solar prominence, using the hydrogen line. Hale in 1890 by adding a second slit in front of the photographic plate developed and perfected an instrument, the spectroheliograph, by means of which the prominences can now be photographed at any time, and a composite

photograph of the prominences, faculæ, and entire solar surface built up.

10^h 40^m A.M. 10^h 58^m A.M.

FIG. 15. THE SOLAR PROMINENCE OF MARCH 25, 1895, AS PHOTOGRAPHED BY HALE

These prominences are projections from a layer of permanent gases surrounding the photosphere. Among these gases hydrogen is the most conspicuous and it gives to the prominences their brilliant red colour, and to the layer of gases its name, *chromosphere*. The average depth of this layer is from 5,000 to 6,000 miles. From it the prominences arise, reaching an average height of some 30,000 miles, and occasionally attaining the immense altitude of 150,000 miles. On October 7, 1880, Young measured a prominence and found it to extend 350,000 miles

beyond the edge of the sun. These protuberances not only differ in size, but also in character. Some float quietly above the chromosphere, resembling great clouds and remaining unchanged for days. These are the "quiescent" prominences. They are found on all parts of the sun and often attain great size, but never a great altitude. Like the clouds in the earth's atmosphere, these hydrogen clouds assume all sorts of fantastic shapes, but, unlike atmospheric clouds, they are usually joined to the chromosphere by long slender filaments.

Sharply distinguished from these cloudlike forms are the "eruptive," or, as Secchi calls them, the "metallic" prominences. These undergo rapid changes in shape and size, and appear as though caused by violent upheavals or eruptions. The great prominence observed by Young and mentioned above was of this class. When first seen at 10.30 A.M. it was about 40,000 miles high and of ordinary appearance. Half an hour later it had doubled its height, and by 12 o'clock it had reached its greatest development. By 12.30 it had crumbled away and disappeared. During the hour of most rapid change, this prominence shot upward with a speed of 75 miles a second. Great as this speed may appear, prominences have been observed in which velocities of 250 miles a second have been found. Velocities of 100 miles a second are by no means uncommon. The prominences, themselves, take on all sorts of fantastic shapes, appearing at times like writhing flames, at others like the coloured

jets of an electric fountain. They generally last but a few moments, half an hour often embracing the entire period of their development and final disappearance.

The spectroscope indicates that these eruptive prominences contain many of the elements found in the sun itself; the lines of sodium, iron, and calcium, besides those of the ever-present hydrogen have been frequently observed. Most of these elements, however, are confined to the base of the eruption, the extreme upper portions being composed merely of hydrogen. They appear to be intimately connected with the formation of spots, usually appearing in those portions of the sun where spots are to be found, and rarely occurring in any other region.

Far out beyond the region of the faculæ and prominences stretches the enveloping *corona*. This halo, seen only at total solar eclipses, has been known for centuries; and yet to-day its real constitution is nearly as unknown and mysterious as it was at the time Plutarch described its beauty. In general it appears as a brilliant white oval surrounding the black disc of the moon; the long axis of the oval being nearly parallel to the sun's equator. It is made up of streamers and rays, dazzlingly bright near the edge of the disc, and fading gradually away until they become imperceptible. So faint and indistinct are the outer portions of the corona that it is impossible to draw any definite outline. Its character is such that its appearance depends to a great extent upon the

condition of the atmosphere, a slight haze rendering the outer portions invisible. As a rule, however, the streamers can be traced to a distance equal to the sun's radius, and occasionally they have been observed to extend for five or six degrees from the sun's edge, a distance of several millions of miles.

The equatorial streamers are usually long broad bands of light, somewhat curved in toward the plane of the equator. The polar rays, on the other hand, are more frequently short and narrow, and bend away from the axis. Plate 4 is from a photograph taken by Campbell and Perrine in the eclipse of 1905 and is one of the best representations of the corona yet obtained.

Many attempts have been made to photograph the corona independently of an eclipse, but so far all such attempts have resulted in failure. The most elaborate of these attempts were those of Huggins in England and of Hale in this country. Huggins tried the direct photographic method, using a reflecting telescope and cutting off the direct light of the sun with a screen. For some time it appeared as if this process might be successful. Many plates were obtained which had halos resembling the corona. But after careful investigation these proved to be due to irradiation, and to "ghosts"; to optical and photographic defects. Hale tried a spectrographic method, somewhat similar to that so successfully tried on the prominences and faculæ. Although in order to secure clear atmosphere he carried his apparatus to

The Corona as Photographed by the Lick Observatory Expedition of 1905

Pike's Peak and to Mount Ætna, yet this most promising method failed to give any definite results. Thus the study of the corona is limited to the few brief moments of total solar eclipses; to some five or six minutes every few years. For this purpose expeditions are fitted out and sent to the most favourable locations; and the astro-physicist utilises every moment of totality in obtaining photographs and spectrographs for measurement and study. The last favourable eclipse occurred on August 30, 1905, and was widely observed. The next eclipse which can be utilised will occur on October 10, 1912, and will be observable in South America.

The corona is made up of an intricate system of rays and streamers. The polar rays are short and curved and somewhat resemble the representations of lines of force in a magnetic field. The streamers stretch out to far greater distances and are generally connected with those regions of the sun in which active prominences occur. These streamers are often curved and interlaced, and their forms differ radically at different eclipses. The form of the corona seems to undergo periodic changes, and these changes appear to be connected with the general eleven-year cycle of solar activity.

The spectroscope shows that the light of the corona is partly reflected sunlight and partly native light, due to the presence of incandescent gases. The corona probably consists of minute solid, liquid, and gaseous particles; matter ejected from the sun,

meteoric matter, and minute dust-like planets. Whatever the exact condition of this matter, it is exceedingly rare, for several comets have passed directly through it without suffering the slightest changes in their motions. Arrhenius has computed that the amount of matter in the corona is equivalent to a single dust particle in every fourteen cubic yards.

The application of the spectroscope to the study of eclipses of the sun has been made notable by a long and interesting series of discoveries. The first eclipse at which the spectroscope was used was that of 1868 observed by Janssen in India, when it was seen that the spectrum of the prominences was a series of *bright* lines, thereby proclaiming with no uncertain note that these red flames consisted of burning hydrogen gas. So brilliant were the spectral lines that Janssen looked for them the next day, when there was no eclipse, and found them readily enough.

At the eclipse of the next year, 1869, the spectroscope revealed a prominent bright line in the yellow near the two D lines of sodium. From the position in the spectrum the line was given the name D_3, and as no known earthly element produced this line, it was called a helium line. Not until 1895 did the great English chemist Ramsay find helium present in small quantities in the mineral cleveite.

Before the eclipse of the next year, 1870, Young foretold a startling phenomenon that might be seen in a spectroscope if one looked closely for it. If the sun were a brilliant orb of fire without any cooler

gases around it, its spectrum would be a band of coloured light unbroken by any dark lines. However, when the light of the sun passes through the envelope of cooler vapours that surround it, certain waves are absorbed and the sun's light reaches the earth *minus* the rays or colours absorbed. This thin stratum of gases which produces the absorption causing the dark Fraunhofer lines has been called by Young the "reversing layer." Although cool in contrast to the sun itself, nevertheless the gases in it are at a very high temperature. At the instant that the sun's surface is entirely covered up by the moon at the time of a total eclipse, the reversing layer makes itself visible in the spectroscope. The spectrum of the hot gases consists of a series of bright lines. At the eclipse of 1870 Young saw the whole solar spectrum with its thousands of dark lines changed in the twinkling of an eye to a spectrum of bright lines. The change was so sudden and so remarkable that the new bright-line spectrum was called the "flash spectrum." This was photographed for the first time at the eclipse of 1896 by Shackleton. Since then there have been the eclipses of 1898, 1900, 1901, and 1905, and at each succeeding eclipse advances were made and better photographs obtained. The most successful photographs are those of Mitchell taken in Spain, August 30, 1905. These photographs, obtained with a grating ruled on a parabolic surface, are of exquisite definition and contain about five thousand lines between $\lambda 3300$ in the ultra-violet and

Fig. 16. The Flash Spectrum, photographed by Mitchell at Daroca, Spain, Aug. 30, 1905.

the C line at the red end of the spectrum. These photographs will settle many interesting problems regarding the gases which are found in the chromosphere and the heights to which these gases extend above the sun's surface.

CHAPTER VI

THE SUN'S LIGHT AND HEAT

ALL questions concerning the light and heat of the sun have an intense interest, for upon the steady and regular maintenance of the amount of heat received by the earth depends the very existence of life upon our planet. Any large variation in the amount of solar heat received would totally destroy the world as it is to-day, would make it an uninhabitable furnace or a frozen waste of icebergs. Important and far-reaching as investigations upon such matters may be, yet it is only within comparatively recent years that they have been recognised as forming a great branch of astronomy. A hundred years ago so little was known about heat and its properties that the elder Herschel could advance his fanciful and utterly impossible theory of a habitable sun.

Light and heat are but different manifestations of the same kind of energy. Originating in the molecular velocity of a substance, this radiant energy is distributed throughout space in the form of waves, or pulses, which travel, through the ether, with a velocity of 186,000 miles per second. Just as the waves of

the ocean vary in size and length, so vary these light and heat waves. A light summer zephyr ruffles the ocean's surface with ripples two or three inches high and but a few inches apart; a heavy and long continued gale causes immense rollers, which extend from horizon to horizon and are hundreds of yards from crest to crest. While the ocean waves are thus measured by feet, and by yards, the regular rhythmic pulses of radiant energy are measured by minute fractions of an inch. The longest recognisable heat wave, when measured from crest to crest, is but 0.03 millimeter, about one one-thousandth of an inch long. More than one hundred thousand of the shorter waves could be crowded into a single inch. A special unit, the micron, is used to measure the length of the waves. This is the one thousandth part of a millimeter, which corresponds to, approximately, one twenty-five thousandth of an inch. The radiant energy emitted by an incandescent body like the sun is composed of an infinite number of waves, piled one on top of the other, and varying in length from a small fraction of a micron to several microns. The very short waves are invisible and make their presence known by the chemical action they exert upon the photographic plate. These are known as the ultra-violet waves. The portions of these waves which affect the optic nerves and convey to our brains the sensation of "light" are the spectrum colours violet, indigo, blue, green, yellow, orange, and red. The length of these waves from crest to crest ranges from 0.4 to 0.7 of a

micron. The waves whose length exceeds this latter limit are invisible and are known as the invisible heat or infra-red rays. The waves producing light are so tiny and proceed with such rapidity that moving along on a sunbeam 3,000,000,000,000,000 or 3x10^{15} waves of yellow light enter the eye in a single second of time. Thus only a very small part of the total radiant energy of a body produces the sensation of light, but all the rays may be made effective as heat; when absorbed by a body they all aid in raising its temperature. In other words, all rays are heat rays, but only a very few of the heat waves produce light.

Measurements of the quantity and intensity of the *light* emitted by the sun, therefore, will give a very imperfect idea of the vast energy given out by that body. While such measurements are of no vital importance, yet they are interesting and enable one to form a rough idea as to the intensity of the solar radiations. In comparing artificial lights it is usual to use as a standard a specially made pure sperm candle that weighs one sixth of a pound and burns 120 grains an hour. An ordinary gas burner gives a light equal to some ten or twelve such candles; an incandescent electric light is equivalent to sixteen standard candles and is ordinarily spoken of as a light of "sixteen candle power." There are a number of ways of comparing the intensity of two lights, one way being to place the two lights at the opposite ends of a long table, or "optical bench," and then to find the point between them that is equally illuminated by both. If

this point be exactly half way between the two lights, they are equal; if nearer one, then the opposite light is the stronger. If the point of equal illumination be one yard from the first light and two yards from the second, then this latter light will be four times as powerful as the first, for light decreases with the square of the distance. Now the quantity of light which we receive from the sun can be compared to the standard candle, and this quantity is found to vary very much with the position of the sun in the heavens. When the sun is near the horizon much less light is received than at noontime. The atmosphere of the earth absorbs the light. At morning and evening the rays pass diagonally through the atmosphere, thus passing through a much thicker atmospheric blanket than they do at noon, and are to a greater extent absorbed. Now when the sun is in the zenith, and the rays pass perpendicularly through the atmosphere, it is found that the sun's light is equivalent to that of sixty thousand (60,000) candles at a distance of one yard. When allowance is made for the atmospheric absorption this figure is increased to nearly 75,000. But the sun is 164,000 million yards distant, and hence the candle-power of the sun is $(75{,}000) \times (164{,}000)^2 \times (1{,}000{,}000)^2$, a number so large as to be utterly incomprehensible.

Not only is the total candle power of the sun so immense, but so also is the intensity of its light. The total surface of the sun is approximately $4\pi \times (1760)^2 \times (440{,}000)^2$ square yards, and dividing this

into the former figure it will be seen that each square yard of surface is as bright as 250,000,000 candles, or each square inch shines with a brilliancy of over 100,000 standard candles. The light is many times more brilliant than the calcium light, three or four times that of the intensely brilliant "crater" of the electric arc. The nucleus or blackest part of the darkest sunspot is brighter than the most brilliant artificial light that we know of on earth.

Far more accurate and satisfactory estimates may be made of the total energy or "heat" received from the sun. Estimates of the amount and intensity of any light depend upon a visual comparison, and the human eye is notoriously inaccurate and liable to deception. Quantities of heat on the other hand can be accurately measured and stated in precise and well-known terms. Quantity of heat must be carefully distinguished from temperature. It takes twice as much heat to raise a quart of water to the boiling point as it does for a single pint. The temperature of the quart and the pint may be the same, but the quantity of heat in the quart will be the larger. Heat is a mode of motion, and temperature is a measure of the intensity, of the quality, not of the quantity of motion.

The measure of quantity used in heat determinations is the "calorie": the amount of heat required to raise one kilogram of water one degree centigrade. This is a perfectly definite unit whose equivalent in mechanical energy is well known. For many pur-

poses, however, a small calorie is used; this is the amount of heat required to raise one gram of water one degree, and it is therefore one one-thousandth that of the large or engineering calorie. Some writers use one unit, some the other. Langley prefers to use the small calorie.

Now it is not a very difficult matter to measure at a given point on the earth's surface the approximate number of calories received from a beam of sunlight of known dimensions. A beam of sunlight of definite and known cross section is allowed to fall perpendicularly upon a vessel containing a known weight of water. In the water is a delicate thermometer and the rise of temperature per minute is noted. The upper surface of the vessel which is exposed to the sun must be roughened and covered with lamp-black, so that it will readily absorb all the heat and light which falls upon it. Many precautions must be taken to prevent the water from being heated by radiations from surrounding objects, or from losing its heat to those objects. Such experiments were made by the younger Herschel at Cape Town as early as 1838 and by Pouillet in France at about the same time, and gave fairly accurate estimates of the quantity of heat derived from the sun. Herschel found that a beam of sunlight three inches in diameter would raise the temperature of 4638 grains (about half a pint) of water 0.37 of a degree per minute. At the time these experiments were made the sun was some 12° from the zenith, and from these Herschel concluded that,

were the sun in the zenith, the amount of heat received would melt a coating of ice one inch in thickness in two hours and thirteen minutes. This is the equivalent of about twelve calories per square metre, a quantity which is now known to be considerably too small.

The greatest difficulty in arriving at a correct conception of the amount of heat received from the sun lies in the fact that all such measures must be made at the earth's surface. Before reaching the apparatus the sun's rays pass through many miles of atmosphere; the heat and light are absorbed and only a small portion of the original energy of the rays actually reaches the surface and becomes effective in heating the water of our apparatus. An approximate idea of the absorption may be obtained by measuring the amounts of heat received from the sun at different hours of the day. The path of the ray through the atmosphere can be calculated at any time, and its length relative to the height of the atmosphere computed. When the sun is just rising or setting, its horizontal rays pass through several times as many miles of atmosphere as when directly overhead at a tropical noon. But the amount of heat absorbed by the atmosphere is not directly proportional to the length of the path; it depends rather upon the mass of air passed through. Two layers of different thickness, but each containing the same mass of air, will absorb the same proportionate amount of energy from the rays passing through them. And each suc-

ceeding layer of similar mass will absorb the same proportionate amount. If the first layer absorbs half the energy and transmits half, then the second layer will absorb one half of the energy incident upon it and will also transmit half, or will transmit a half of a half, or one quarter of the original amount. Three such layers would transmit one eighth, and four one sixteenth of the full amount. The percentage of the ray of heat or light absorbed by passage through unit thickness of air, or other absorbing medium, is called the "coefficient of absorption," and its value can be found by measuring the relative amounts transmitted through any two strata of known and widely different thickness or mass. As soon as this coefficient is known the amount absorbed by a layer of any thickness can be readily calculated.

Now the early investigators of the sun's light and heat assumed in their calculations that a single coefficient could be used, that the various rays of different colours and wave-lengths were all absorbed somewhat in the same proportion. They knew, however, that this was not correct, that different wave-lengths are absorbed differently, but thought that they could find and use an average coefficient and that such average coefficient would give practically correct results. In this way it was generally estimated that, in average fair weather, by the time the sun's rays reached sea-level there had been absorbed by the atmosphere about twenty (20) per cent. of the total

energy. Pouillet made this 18 to 24 per cent., Müller 17, and Pritchard 21.

With this value of the atmospheric absorption Pouillet determined the "solar constant," or the quantity of heat received by each square metre at the upper surface of the earth's atmosphere, to be 17.6 calories, Crova estimated it at 23.2, and still later Violle 25.4 calories.

Langley showed that the amount of atmospheric absorption had been greatly underestimated and that probably nearly forty (40) per cent. of the sun's energy failed to reach the surface of the earth directly. He found the method of treating the rays " en masse " and using an average coefficient of absorption is erroneous, and that it always gives a result which is too small. For example he divided the solar spectrum into ten divisions and found the coefficient for each separate part. These coefficients varied to a marked extent, but from each he could find the amount of heat absorbed for the corresponding division or part of the spectrum. By adding up these ten separate amounts he found that over 41% of the total heat was absorbed by the atmosphere. By taking totals only, or by finding the lump or gross coefficient, the absorption would apparently amount to only 20 %.

The solar energy is the sum of an infinite number of radiations, which are influenced by the atmosphere in an infinite number of ways. Dust and larger particles in the atmosphere reflect the heat and treat all

the rays alike. Smaller particles like dust act more selectively, affecting the rays in one part of the spectrum more than in another. The effect of the larger particles is to produce a general and almost indifferent absorption: the effect of the molecules is to cut out some kinds of light and heat and not others and thus to fill the spectrum with dark atmospheric lines. After passing through the atmosphere the solar light and heat is thus not only less in amount, but different in kind.

Thus in order to arrive at correct results the amount of heat transmitted by each separate wave-length in the solar spectrum should be measured. This is evidently an impossibility. Langley, however, devised an instrument, the "bolometer," which goes far toward realising this ideal condition. With it can be measured the amount of heat in an extremely narrow bundle of rays and the spectrum explored from end to end. What is brightness to the eye is heat to the bolometer and what is blackness to the eye is cold to this most delicate instrument. In a heat map of the solar spectrum the familiar dark lines and bands appear as cold lines and bands. In principle the bolometer is very simple: it depends upon the fact that the electrical resistance of a metal is increased by heat; the hotter the metal, the more difficulty an electric current encounters in passing through it. If now a current of electricity be divided and pass to a differential galvanometer by two wires of equal length and cross section, the needle of the galvanometer will re-

main stationary. When, however, one of the wires is heated, its resistance is increased, it becomes a poorer conductor, and a greater portion of the current at once flows through the easier channel. This change is indicated by the sensitive needle of the galvanometer, which moves by an amount proportional to the energy in the ray which heats the wire. In the complete instrument a portion of each wire is removed and thin strips of steel or platinum substituted, and the heat is applied to one of these strips. The strips are about $\frac{1}{400}$ of an inch wide and $\frac{1}{10,000}$ of an inch thick. One strip is placed in the axis of an ebonite cylinder, the other very close to the first but not in the axis, so that both are equally warmed or cooled by any change in the temperature of the surrounding atmosphere. At the end of the cylinder is a narrow slit, so that a heat ray travelling in the direction of the axis may pass down the cylinder and fall upon one strip only. The resistance of this one strip is increased and the galvanometer needle moves.

Many improvements have been made to the original instrument by both Langley and Abbott, until now the bolometer is so delicate that differences of temperature of less than one hundred-millionth of a degree can be detected. The ordinary thermometer can detect changes of temperature amounting to rough fractions of a degree; delicate thermometers, changes of perhaps one hundredth of a degree. The bolometer is thus a million times more sensitive than the best thermometer. Not only is the instrument

thus extremely sensitive to minute amounts of heat, but in the accuracy of its measurement it compares favourably with the best astronomical instrument. The probable error of a heat determination is less than two one-hundredths of one per cent.

With this instrument Langley measured the relative heat of various wave-lengths and mapped the solar spectrum far down in the infra-red to wave-length 0.0053 mm. (5.3 μ). He carried on his researches at sea-level and at an elevation of 15,000 feet on Mt. Whitney, California. By comparing the relative distribution of heat in bolographs, taken at high and low sun respectively, he found the atmospheric absorption corresponding to different wave-lengths of radiant energy. There is an enormous systematic or general absorption, increasing toward the ultra-violet and diminishing toward the infra-red. The absorption on the whole grows less and less as the wave-length increases. But in the lower spectrum, far down in the infra-red, there appear great bands of local absorption, spaces where for a few wave-lengths the energy is almost completely cut out by the atmosphere. So strong is the local, or selective, absorption at these points, that even on the tops of mountains these cold telluric bands appear and a great many rays are totally extinguished long before they reach the earth's surface.

After allowing for this atmospheric absorption Langley found the distribution of heat or energy in the solar spectrum as shown in the accompanying

diagram. The scale of wave-lengths is laid off on the horizontal line; the height of the curve at any

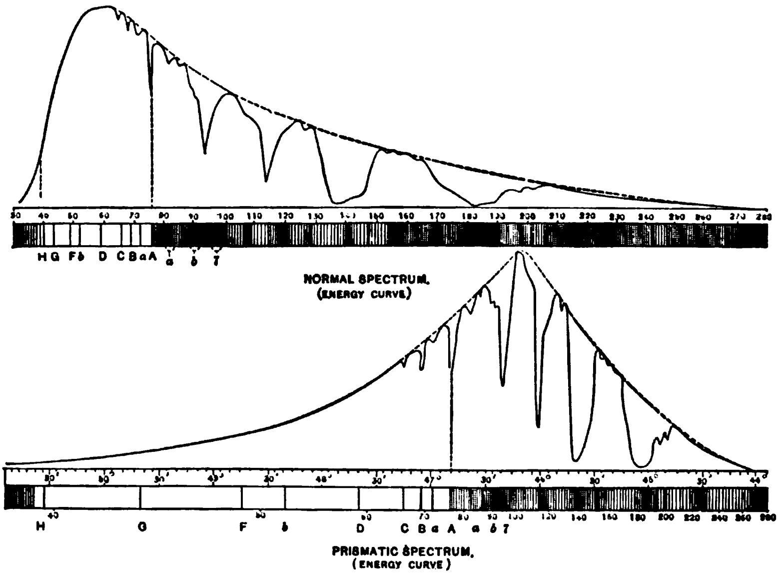


FIG. 17. DISTRIBUTION OF HEAT IN THE SOLAR SPECTRUM.

point represents the relative intensity of the radiation of that wave-length. The maximum intensity is seen to be in the orange and the distribution of energy agrees very approximately with that of light. While the rays of the visible portion of the spectrum are thus the most intense, yet the total energy of the dark rays greatly exceeds that of the visible rays. If the spectrum be divided into three great portions, the invisible ultra-violet, the visible, and the dark infra-red, then the total energy is distributed between these three portions somewhat as follows:

The ultra-violet (invisible) contains $\frac{1}{100}$ or less.
The visible spectrum contains $\frac{1}{5}$ approximately.
The infra-red (invisible) contains $\frac{4}{5}$ approximately.

The absorption in the atmosphere modifies the character of the radiation received and the apparent colour of the sun. The rays of short wave-length are absorbed to a greater extent than those of long wave-length. The relatively low intensity of the radiations of great wave-length is due not so much to absorption as to the fact that the intensity is small. The relatively great intensity in the luminous part of the spectrum exists, then, not on account of feeble absorption, but in spite of a strong absorption. To one situated outside of our atmosphere the sun would appear bluish, instead of a deep yellow.

From the observations at Mt. Whitney, Langley determined the solar constant to be thirty-six calories. More recent observations made by Abbott in the Astrophysical Observatory of the Smithsonian Institution at Washington and at Mt. Wilson, California, show this value to be high. Thirty calories is now considered as closely approximating the true value. This is heat enough to melt a sheet of ice nine tenths (0.9) of an inch thick every hour. Thus the earth receives hourly enough heat to melt a circular disc of ice nine tenths of an inch thick and nearly eight thousand (7920) miles in diameter. In a year the solar rays would melt a disc 657 feet thick. As the area of the earth's surface is equal to

the area of four great circles, this disc of ice, if spread out over the entire surface, would form a shell some 164 feet thick. This shell the sun would melt annually, provided its heat were uniformly distributed. The equatorial regions, however, receive much more heat than do other portions of the globe, and there the sun's rays are sufficient to melt a belt of ice some 209 feet thick, annually. In high latitudes the shell would be much less than the average (164 feet) thickness.

The tremendous amount of energy received from the sun may be illustrated in another way. Ordinary steam engines, whether for railroad or factory use, are rated by their horse-power; a hundred-horse-power engine will drive a small steamer or operate a mill of some two hundred and fifty looms. Now thirty calories of heat per minute, if completely utilised, would produce 2.8 horse power. Neglecting atmospheric absorption, therefore, each square meter of the earth's surface receives from the sun, when directly overhead, sufficient energy to run a 2.8 horse-power engine; or one horse-power is received for every four square feet of surface. The absorption of the air cuts this down about forty per cent. so that on a clear day at sea-level, with the sun directly overhead, sufficient energy to produce one horse-power is received on each six and a half square feet of surface. Several attempts have been made to utilise this solar energy and make the sun drive machinery for practical purposes. The most successful of these attempts was that of Ericsson, who constructed a giant reflector and

concentrated the sun's rays upon a small boiler, in which steam was generated and afterwards used in an ordinary engine. He ran, during fair weather, a three-horse-power engine, developing one horse-power from one hundred square feet of reflecting surface. In other words Ericsson succeeded in turning about one fifteenth of the theoretical amount of solar energy into available power.

Taking the world as a whole, after allowing for atmospheric absorption, each twenty-eight square feet of surface should produce continuously, in a perfect engine, one horse-power. The energy falling upon an ordinary city lot should run continuously a hundred-horse-power plant. If all the coal deposits in Pennsylvania were burned in one second, they would not produce as much power as the sun furnishes us in the same time. The difficulty in the practical utilisation of the solar energy lies in its extreme variability. In the morning and afternoon, when the sun is low in the heavens, but a small amount of energy reaches the surface and even at noon a passing cloud will absorb the greater part of the solar radiation. In order that a cotton mill may pay dividends, its machinery must run at maximum speed from six o'clock in the morning until closing time at night, and must run thus day after day, rain or shine. Until a cheap and perfect system of storing up surplus energy is devised, the solar engine cannot come into general use.

The amount of energy received from the sun is constantly fluctuating, it varies from minute to minute

and from hour to hour. The greater part of this variation is due to changes in the earth's atmosphere, causing more or less of the energy to be absorbed; but later investigations seem to show that there is a real variation in the solar constant. It would appear that at times the sun radiates more heat than at others, and this variation in the solar radiation Langley and Abbott explain by changes in the depth and density of the sun's atmosphere. Experiments show that the heat radiated by the solar disc varies from the centre outward, the radiation from the centre being very much more intense than that from the edges. Langley and Abbott find a steady diminution from centre to edge, until near the edge the radiation is reduced to less than half that from the same extent of surface near the centre. This is due to absorption in the solar envelopes; the light and heat from the edge, passing diagonally through a greater depth of the solar atmosphere, are much more strongly absorbed than that from the centre. These envelopes are more transparent to the red rays than to the violet; the solar atmosphere changes the colour, as well as diminishes the quantity of light that is transmitted through it. If the sun's atmosphere were removed, the sun would take on a decidedly bluish tinge and its brightness would be increased several fold.

Langley and Abbott show that small changes in the transparency of the solar atmosphere would cause large fluctuations in the solar constant and cause sen-

sible changes in meteorological conditions on the earth. A large value of the solar constant indicates that the earth is receiving more than the usual supply of energy from the sun, and, taken as a whole, therefore, the world should be warmer. If the solar constant be below the average, the earth should be colder. In this way it may be possible some day to predict the general character of the seasons through a careful and continuous study of the solar radiations. The observations for determining such variations are attended with great difficulty, the variations due to local conditions in the earth's atmosphere being so very much greater that they almost completely mask the real solar fluctuations. The new solar observatory of the Carnegie Institute on Mt. Wilson, above the main body of our atmosphere, is very favourably situated for investigations upon the amount and character of the solar radiations and its superb equipment is especially designed for such work.

Tremendous as is the amount of energy received by the earth, it is but a minute fraction of the solar output. As viewed from the sun the diameter of the earth is but 17″.6 and it would take over 73,600 bodies the size of the earth to form a narrow belt around the ecliptic, and more than two thousand million earths to form a complete shell around the sun. If the sun radiates its heat equally in all directions, then less than one one-hundred-millionth of the whole is received by the various bodies in the solar system. The rest is radiated out into space and may ultimately reach the

distant stars and nebulæ. If the sun were surrounded by a spherical shell of ice nine tenths of an inch thick and 186,000,000 miles (the diameter of the earth's orbit) in diameter, such a shell would be entirely melted in an hour. Now, the surfaces of spheres are proportional to the squares of their radii, and the thickness of such an hypothetical ice shell which could be melted in one hour would be increased in this ratio as its diameter is reduced. The radius of the sun is about $\frac{1}{215}$ that of the earth's orbit, and hence, in one hour, the heat of the sun would melt a shell, which just encloses that body, some 46,000 times as thick as that at the distance of the earth. At the earth the thickness of the shell is 0.9 inch and at the sun's surface, therefore, the thickness would be some 41,400 inches or 3460 feet. In other words, if the sun were frozen over to the depth of one mile, the entire mass of ice would be completely melted in one hour and thirty-one minutes. Each square foot of the sun's surface radiates over 110,000 calories per minute; radiates sufficient heat to develop continuously over 10,000 horse-power.

Various tests show that the total heat of combustion of one pound of the best anthracite coal is about 3,000 calories. To maintain the heat radiated by each square foot of the sun's surface would require, therefore, the combustion of thirty-three pounds of coal each minute; or one ton each hour. In an ordinary boiler plant from twenty to thirty pounds of coal per square foot of grate surface are consumed in an hour. The solar radiation is thus fifty times more powerful

than the fire under an average boiler and many times more powerful than that of the best blast furnace. Now a ton of anthracite coal occupies about thirty cubic feet of space, so that in order to have a ton per square foot of surface, a layer would necessarily be thirty feet thick. If then the sun were solid coal and were burning in pure oxygen, a layer thirty feet in thickness would be consumed each hour, and the diameter of the sun would be reduced by fifty-two miles each year. As the sun grew smaller a greater thickness would be consumed each year and a simple calculation shows that the sun would be entirely burnt up in about five thousand (5000) years. Historical records run back for more than five thousand years and geological formations and fossils show us that the earth has existed for many millions of years. The heat of the sun, therefore, cannot be explained by combustion, nor can that body be a heated solid cooling down. For the temperature of such a cooling body would fall at a rate sufficiently great to be noticeable after the lapse of a few centuries, and no perceptible diminution in the amount of solar heat has taken place since recorded history began.

Two reasonable theories have been advanced to account for the maintenance of the solar radiation: one, the meteoric hypothesis of Mayer; the other, the more generally accepted theory of Helmholtz.

When a moving body is stopped its energy of motion is transformed and appears as heat; the lead bullet from a pistol is melted when it strikes against an iron target. There is an exact mathematical relation

between the amount of heat produced and the mechanical energy of the moving body; so that if the mass and speed of the body be known the amount of heat that will be produced by its stoppage can be accurately calculated. It makes no difference whether the stoppage be sudden or gradual, the amount of heat produced is the same, but the temperatures will vary widely. When the body is suddenly stopped the whole amount of heat is instantly released and the temperature of the body and its surroundings is raised to a high degree; when the body is gradually brought to rest, the heat is slowly evolved, and the body may radiate this heat as fast as it is produced and when the body is finally brought to rest its temperature may be no higher than at the start. The quantity of heat thus generated by a moving body increases proportionally to the square of the velocity; if the speed of the body be doubled, the amount of heat produced will be quadrupled. A body weighing one kilogram (2.20 pounds) and moving at the rate of 91.3 metres (299.54 feet) per second will, if stopped, produce just one calorie of heat. Now, a body in falling from a great distance to the earth would acquire a velocity of 6.94 miles, or 10,240 metres, per second. This velocity is 112 times that required for a kilogram to produce one calorie, and a body of similar mass moving with this speed and stopped by the earth, or by the friction of the atmosphere, would therefore produce over 14,800 calories, a quantity of heat sufficient to completely vaporise it. A body of

similar mass falling from infinite space to the surface of the sun would attain a velocity of 380 miles per second and would produce over forty-five million (45,000,000) calories. One kilogram of pure carbon when burnt in oxygen produces only about 8000 calories. Hence by its fall into the sun a kilogram of matter will produce over five thousand times as much heat as would an equal mass of carbon when burnt under the most favourable conditions.

In this way it is easy to calculate, as did Lord Kelvin, that if the earth fell into the sun it would supply heat enough to maintain the supply for ninety-five years, and that, if the entire planetary system collapsed upon the sun, there would be liberated sufficient heat to supply the solar furnaces for over 46,000 years. Thus, if there should annually fall upon the sun from outside space a quantity of matter equal to a little less than one one-hundredth of the mass of the earth, the supply of solar energy would be continuously renewed.

Undoubtedly a quantity of meteoric matter does fall into the sun and a certain portion of its heat is thus maintained. But it would hardly seem possible that any large part of the heat is due to this cause, for if there were sufficient meteoric matter falling into the sun, the earth would encounter many more meteors than it does. The earth revolves about the sun and accompanies that body in its passage through space, and if there is any great rain of meteors upon the sun, the earth should receive its proportionate

share. It has been shown by Pierce that if the meteoric matter is abundant enough to cause the solar heat, the earth would annually receive nearly fifty tons upon each square mile of surface. No such amount is received, nor even an appreciable fraction of that amount. This is known not only by direct observation, but also by the indirect effects that such meteoric deposits would cause. A vast number of meteorites falling on the earth's surface would change the period of rotation of the earth upon its axis and lengthen the day. From the time of the first recorded observation the day has not been lengthened by so much as one one-hundredth part of a second, and hence it may be safely concluded that the amount of meteoric matter actually deposited is comparatively small.

The contraction theory of Helmholtz, which is now generally accepted, differs from the meteoric only in substituting, in place of the meteors, the sun itself. The sun is gradually falling into itself, the outer layers are falling toward the centre; the sun is shrinking, growing smaller; and this contraction, this falling in of the outer particles, produces the immense outflow of energy. The whole sun contracts, every particle of its whole mass falls toward the centre and contributes its mite to the total supply of heat. The surface particles move, of course, through a much greater distance than do those within the sphere. On account of the tremendous mass of the sun a very slight contraction will suffice to maintain its supply of heat. A shrinkage in the solar diameter of some 300

feet a year is all that is necessary to account for the great outpour of energy. On the sun's disc a second of arc is equivalent to 440 miles; and, at 300 feet a year, it would take nearly 7000 years for the solar disc to shrink by this amount. No instrumental proof of this contraction theory, therefore, can be expected for many centuries.

In 1870 Lane showed that a mass of gas, if away from all disturbing causes, would contract under the action of its own gravitation and at the same time would continually grow hotter. The amount of heat that such a mass of gas would lose by radiation would be more than counterbalanced by the heat generated by the shrinkage. If, then, the sun be a pure gaseous body its temperature must be slowly rising.

This law of Lane's does not apply to a solid or liquid body. Such a body can contract but little and radiates heat faster than the supply can be kept up by the shrinkage, and therefore the body rapidly cools off. So far as can be determined the sun's temperature is nearly if not quite stationary, and this would indicate that it is neither purely gaseous, nor wholly liquid or solid, but in an intermediate state, part gaseous and part liquid, or that it is in such a state of pressure and density that the ordinary laws of gases no longer apply. Evidently, however, at some future time, the sun will pass from the gaseous, or semi-gaseous, into the liquid stage and from that moment it will begin to lose temperature rapidly. There is, therefore, a definite end in sight, a time beyond which

the sun will cease to shine and the world, as it now exists, will come to an end. Any estimates as to when this will occur can be the roughest kind of approximations only, and merely serve to show the inevitable conclusions. Newcomb thinks that within ten million years the sun will have cooled to such an extent that life will have ceased to exist on the earth.

The heat radiated by the sun warms all bodies upon which it falls; the temperature of the earth is raised and it is made habitable by the energy derived from the sun. Now a body receiving heat from the sun may reflect or absorb that heat. Some bodies reflect the heat rays that impinge upon them, others absorb them: a bright, polished metal surface reflects the greater part of its rays; a rough, uneven, blackened surface absorbs nearly all the heat that falls upon it. A body which absorbs heat readily radiates it readily, and a body which absorbs all the heat that falls upon it is called a " black " body. Such a black body radiates all the heat that it receives and its temperature is due solely to the source from which it receives the heat and its distance from that source. Poynting has calculated the temperatures of such black bodies at various distances from the sun and finds them as in the following table; in which the temperatures are given in Fahrenheit degrees:

Distance from Sun	Temperature
3¾ million miles	2190°, cast iron melts
23 " "	770°, lead melts

Distance from Sun	Temperature
Distance of Mercury	410°, tin melts
" " Venus	176°, alcohol boils
" " Earth	80°, summer temp.
" " Mars	–22°, ammonia boils
" " Neptune	–360°, air liquefies

The average temperature of the earth does not differ radically from what it theoretically should be according to this table. This would indicate that the earth acts sensibly as a black body, it absorbs and radiates freely the heat received from the sun. It is probable that the circulation of the atmosphere greatly aids in this free distribution and radiation of heat over the surface.

CHAPTER VII

THE MOTIONS OF THE PLANETS

AS a whole the heavens appear to-day exactly as they appeared to Hipparchus and to the priests of ancient Babylon. Year after year the stars retain their same relative positions on the celestial sphere, appear to be bound together by some invisible tie. This permanency and unchangeableness of the heavens was recognised at a very early date and the more striking groups of stars were roughly classed together and separated into constellations. These constellations for the most part bear some imaginary resemblance to animals, to common objects, or to characters and incidents in the early Greek mythology. So eternal seem these configurations that the stars are commonly spoken of as *fixed* and fixed indeed the wise men of old would have them. They conceived these stars to be set like jewels on the surface of the great celestial sphere, in the centre of which was suspended the earth. It is now known that these figures are not absolutely permanent, that the stars are all in motion, and that gradually as the centuries roll on the groups will change their appearances and the con-

stellations will fade. But these motions are relatively so slow as to be nearly or quite invisible to the naked eye, and appreciable only after the lapse of many centuries. Three thousand years ago the "Great Dipper" was hanging in the northern sky just as it is hanging to-day.

While the great mass of stars thus always appear in the same relative positions, yet from prehistoric times it has been known that seven of the brightest celestial objects are not thus bound together, but appear to wander through the heavens, appearing at times in one constellation, then in another. These seven wanderers, or *planets,* as they have been called, are the sun, the moon, Mercury, Venus, Mars, Jupiter, and Saturn. The motions of the moon are noticeable to the most casual observer; so rapid indeed is her eastward motion among the stars that it can readily be detected in the course of a few hours. In twenty-seven days she completes an entire circuit of the heavens. The motion of the sun is more difficult to detect, for its brilliance is such as to render invisible all stars above the horizon during daytime. By noting the constellations that are on the meridian at midnight, however, the motion of the sun among the stars can soon be determined. These two, the sun and moon, although they thus wander among the stars, differ radically from the other five wanderers and are now no longer classed as "planets."

The five planets known from prehistoric times differ at first sight from the stars only by their apparent

wanderings. Not until the invention of the telescope was their real physical difference known with certainty. And the motions of these five differ radically from those of the sun and moon. These latter move steadily along in their paths, travelling always towards the east, until they have completed a circuit of the heavens. Much more complicated is the motion of a planet. While on the whole each planet moves eastward until it has completed its circuit, yet this motion is not continuous. At times it changes its position in the sky more and more slowly, until finally the planet stops and apparently stands still among the stars. After a while it begins to move again, but now in the opposite direction towards the west, retrograding or retracing part of its former path. However, after moving a short distance to the west, the planet stops and begins again its eastward motion; travelling far to the east before it again stops and repeats the westward swing. During the periods of retrograde motion, the planet describes peculiar loops and S curves among the stars, crossing and recrossing its former path. The eastward swing of a planet is always much longer, both in distance and in time, than the westward.

Two of these planets, Mercury and Venus, never depart very far from the sun, but appear to vibrate across that body, appearing first on one side, then on the other, and accompanying the sun in its annual path around the heavens.

Mercury never reaches a distance greater than 28°

from the sun and, when at its greatest elongation to the eastward of the sun, can be seen in the twilight just above the western horizon. When at its greatest western elongation it can be seen on the eastern horizon, just before sunrise, and to the ancient Greeks was then known as Apollo, the morning star. The accompanying diagram shows the apparent path of

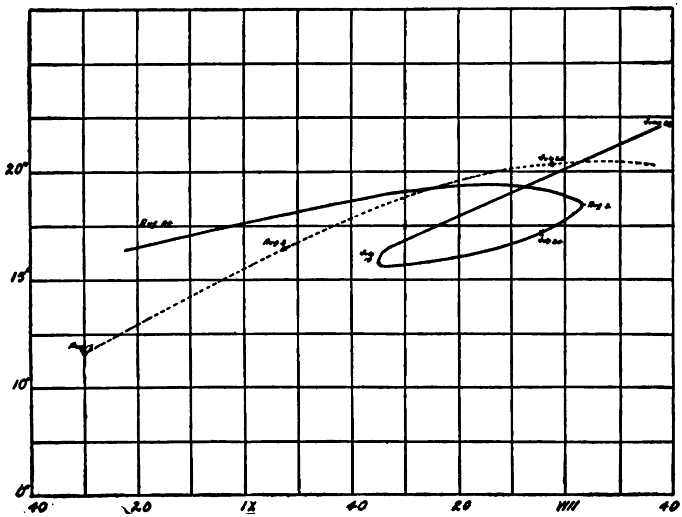


FIG. 18. APPARENT PATH OF MERCURY, 1907

this planet from June 21 to August 24, 1907, the positions of the planet in its path being indicated for various dates. The broken line shows the path of the sun during a portion of the same interval. During June and July, Mercury was to the eastward of the sun and appeared as the evening star; on July 24th the two bodies were in conjunction, and after that

date Mercury was the morning star, being at its greatest western elongation, some 18°, on August 14th. On account of its closeness to the sun it is always quite difficult to catch sight of, but by a little care it can readily be found when at its greatest elongation from the sun. The apparent path of Venus is exactly similar, but its loops are longer, and it reaches a much greater distance east and west of the sun than does Mercury, so that we are all familiar from earliest childhood with the "earth's twin-sister" Venus as the morning and evening star.

The apparent paths of the superior planets, Mars, Jupiter, and Saturn, differ from those of Mercury and Venus in that these planets traverse their respective orbits independently of the sun, sometimes being near that body and just as frequently in opposite parts of the heavens. The characteristic planetary loop of retrogression is, however, present.

For many centuries astronomers sought to explain these curious and at first sight capricious movements of the planets. The early writers naturally thought the earth to be at rest, and these motions to be actual motions of the planets, revolving about the fixed earth as a centre. Eudoxus, as early as 356 B.C., roughly explained them as combinations of uniform circular motions. He recognised that the loops and retrogressions of Mercury and Venus could be represented by motions of these planets in circles whose centres were on the line joining the earth and sun; and similarly that the motions of Mars, Jupiter, and

Saturn could be approximated to by supposing each planet to revolve around a fictitious planet or centre, which centre moved uniformly around the celestial sphere, completing the circuit in the periodic time of the planet. This was the basis of the famous *epicyclic* theory of the planetary motions, which was afterward elaborated by Hipparchus and Ptolemy into a complete and consistent system.

Not until the time of Copernicus, however, was the true explanation of these loops and peculiar curves explicitly set forth. In his great work, *De Revolutionibus Orbium Celestium,* the first copy of which was received by him on his death-bed, May 24, 1543, Copernicus clearly showed that the apparent motions of the planets are not altogether real, but are, to a great extent, due to the motion of the earth. Copernicus was not the originator of this theory. As early as the third century before the Christian era Aristarchus of Samos conceived the idea that the earth rotates upon an axis and revolves about the sun in a circle. But unfortunately his theories and speculations concerning the motion of the earth bore little fruit and were lost sight of in succeeding ages, being occasionally revived, however, in a vague and uncertain manner. Copernicus took these hazy guesses, worked them up scientifically, and based upon them a complete system of astronomy, which explained the complicated planetary motions much more simply than did the orthodox Ptolemaic theory of an immovable earth.

Thus, according to Copernicus, the sun is at the centre of motion and around it revolve in giant orbits the planets Mercury, Venus, the earth, Mars, Jupiter, and Saturn: Mercury being nearest the sun and Saturn the farthest away. The moon was shown to be unique, in that she revolves not about the sun, but about the earth, being a satellite of the latter body. Copernicus thought these orbits of the planets true circles and by them he could explain, as in the above paragraph, the principal eccentricities of planetary motion. But he found many minor irregularities of motion, both in path and in speed, which could not be accounted for by any arrangement of simple circular orbits. These he explained by introducing into his system many of the epicycles of Ptolemy, using in all some thirty-four circles, four for the moon, three for the earth, seven for Mercury, and five each for the other planets. Half a century after the death of Copernicus the true explanation of these lesser irregularities was given by Kepler, who showed that the orbits of the planets about the sun are not circles and that the speed of a planet in its orbit varies from point to point.

This discovery of Kepler was announced in 1609, when his *Commentaries on the Motions of Mars* appeared. He was a student of, and what would now be called the literary executor of, Tycho Brahé. This indefatigable observer had collected during twenty years of active work an immense amount of data: positions of stars, planets, and especially of Mars.

These observations Kepler reduced and from them he plotted the orbit of Mars about the sun. He soon found that the system of circles used by Copernicus represented this planet's motion but very imperfectly. He, therefore, tried other combinations of circles and epicycles, until he finally reached the conclusion that no combination of circles could represent the actual motion of the planet without introducing errors of at least eight minutes (8′) of arc. This was too great a discrepancy to be tolerated and Kepler, accordingly, discarded the use of circles and uniform motion and soon discovered his two celebrated laws of planetary motion, which form the basis of modern mathematical astronomy. These two laws are so important and so easily understood that they are here reproduced. They are:

1. The planet describes an ellipse, the sun being at one focus.

2. The straight line joining the planet to the sun sweeps out equal areas in equal intervals of time.

These laws, discovered in reference to Mars, were afterward found to apply to each and every planet. The first law gives the shape of the path that each planet describes about the sun; the second the speed with which the planet moves in various parts of its path. A planet moves more slowly in that part of its orbit which is farthest from the sun. Both these laws are exemplified in the following diagram, which represents the orbit of Mercury about the sun, on a scale of 22 million miles to the inch. The half major

axis of the ellipse, or the distance C A, is called the "mean distance," and in the case of Mercury is about 36 millions of miles, or $1\frac{5}{8}$ inches on the scale. The sun is not at the centre, but at one focus, S, and the distance C S is about 7.2 million miles, and this

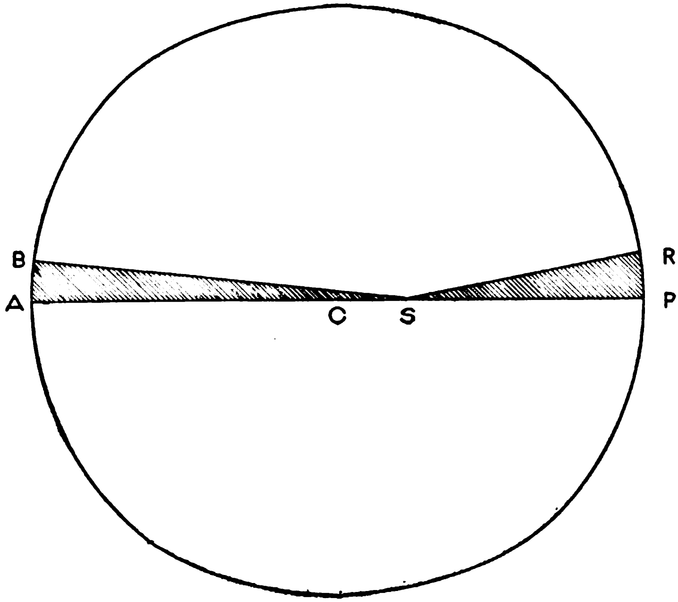


FIG. 19. ORBIT OF MERCURY.

distance between the centre and the focus determines the shape of the orbit. The ratio of C S to C P is called the eccentricity of the orbit, and this eccentricity differs widely for the various planets. When at *Perihelion*, P, Mercury is nearly 15 million miles nearer the sun than when at *Aphelion*, A, the actual distance of the planet from the sun ranging all the

way from $28\frac{1}{2}$ to $43\frac{1}{2}$ million miles. In this elliptic orbit the planet travels about the sun from west to east, moving with widely different speeds; at perihelion Mercury covers a little over three million miles per day; at aphelion somewhat less than two million. According to the second law, however, the planet always moves at such speed that the line drawn from S to Mercury passes over equal areas in equal intervals of time. When at perihelion the planet in two days will pass from P to R, a distance of six million miles; when at aphelion, four million miles from A to B, but the areas of the sectors P S R and A S B are equal. In the diagram these equal areas are shaded.

In the case of the earth the orbit is much less eccentric. On the same scale, the longest diameter of the ellipse would be $8\frac{1}{2}$ inches and the sun would be less than one tenth ($\frac{1}{10}$) of an inch from the centre. The curve differs so little from a circle, that the unaided eye could not distinguish the difference.

Before the time of Kepler many attempts had been made to find the relative distances of the planets from the earth or the sun. It was early recognised that the distance bore some relation to the periodic time in the orbit. Mercury completed her revolution in 88 days, Saturn in $29\frac{1}{2}$ years, and the natural supposition was that the orbit of Saturn is very much larger than that of Mercury. Under the Ptolemaic System the earth was placed at the centre and the planets arranged in the order, the moon, Mercury, Venus, the sun, Mars, Jupiter, and Sat-

urn. Copernicus placed the sun at the centre, and ranged the planets in the order of their periodic times, Mercury, Venus, Earth, Mars, Jupiter, and Saturn, but he did not know the actual dimension of any of the orbits, nor even the proportional sizes. Kepler not only showed that the orbits of the planets are ellipses, but he also determined their distances from the sun in terms of the distance of the earth as unity. He also made many an unsuccessful attempt to obtain a relation between the sizes of the various orbits of the planets and their periodic times of revolution about the sun. After years of vague speculation he published in 1619 the *Harmony of the Worlds,* a book full of worthless nonsense regarding the music of the spheres and fancied relations between the solar system and various musical scales. Although the greater part of this work consisted of such useless vagaries, yet it contained the third great law of planetary motion, the law which binds the various planets together into one great system. This third law of Kepler may be stated as follows:

"The squares of the times of revolution of any two planets about the sun are proportional to the cubes of their mean distances from the sun."

This law is shown by the figures in the following table:

Planets.	Distance.	Cube of Dist.	Period.	Square of Period.
Mercury,	0.387	0.058	0.241	0.058
Venus,	0.723	0.378	0.615	0.378
Earth,	1.000	1.000	1.000	1.000
Mars,	1.524	3.540	1.881	3.538

Planets.	Distance.	Cube of Dist.	Period.	Square of Period.
Jupiter,	5.203	140.8	11.86	140.66
Saturn,	9.539	868.0	29.46	867.9

In this table the distances and times are those known to Kepler and are expressed in terms of the corresponding distance or periodic time of the earth as unity. The numbers in the columns headed "Cube of Distance" and "Square of Period" are practically identical, the discrepancies being well within the limits of error possible at the time Kepler made his researches, and thus he was fully justified in speaking of the law as "precise."

From these three laws Kepler was enabled to draw a correct map of the solar system, to show the relative positions of the planets, and to draw their orbits in their correct shapes and proper relative sizes. But he did not know the actual size in miles of any one of their orbits; in fact, as we have seen,[1] he supposed the distance of the sun from the earth to be only about one fifth of what it actually is.

These orbits of the planets do not all lie in a single plane, but are variously inclined to one another. The plane in which the earth travels about the sun, called the plane of the ecliptic, is taken as fundamental, and the other orbits referred to it. Thus, of the planets known to Kepler, the inclination of Jupiter's orbit is but 1° 18′, while that of Mercury is a trifle over 7°, and the inclinations of the other orbits lie between these limits. Since the invention of the telescope and

[1] Chapter IV. "The Distance of the Sun."

especially during the last century many new planets have been discovered, and of these many have orbits whose inclinations greatly exceed these limits, that of Pallas exceeding 34°. Only two of these discovered planets are of great size, and these two, Uranus and Neptune, lie far outside the orbit of Saturn. Neptune, discovered in 1846, is the outermost planet of the solar system, being some thirty times as far from the sun as the earth, and taking nearly 165 years to completely traverse its immense path. Since the first day of the nineteenth century more than six hundred small planets have been discovered and these form a group, the "Planetoids" or "Asteroids," which move in various paths between the orbits of Mars and Jupiter.

To convey an accurate idea of the dimensions and relative distances of the various bodies of the solar system by means of a chart or diagram is well-nigh impossible. The mechanical contrivances, or orreries, which purport to show the motions of the planets, are more than useless, for they cannot be constructed on anything like an approximate scale. A general impression as to the distances and motions of the planets may be gathered however from the following illustration. On the top of City Hall, New York City, place a great spherical lantern, or searchlight, twenty feet in diameter to represent the sun; then Mercury will be represented by a small plum, on the circumference of a circle 820 feet radius, or at the corner of Broadway and Thomas Street; Venus by

an orange at the corner of Leonard Street, 1550 feet from City Hall; the earth by a large orange at White Street, 2150 feet distant; Mars by a good-sized plum at Grand Street, three fifths of a mile away; Jupiter by an ordinary library globe two feet in diameter, placed two miles away in the middle of Madison Square; Saturn by a slightly smaller globe in the office of the new Plaza Hotel at 59th Street, some four miles from the starting-point; Uranus by a foot-ball on the Athletic Field of Columbia University at 116th Street, and Neptune by a large-size toy balloon in Bronx Park, a little over twelve miles from City Hall. In its orbit about the central luminary, this toy balloon, representing Neptune, will pass over the town of Hackensack, the cities of Passaic, Orange, and Newark, over the hills of Staten Island and the sands of Rockaway Beach, returning by way of Jamaica and Flushing, finally crossing the East River at Whitestone. To imitate the motions of the planets in these orbits Mercury must move at the rate of three feet an hour; Venus not quite two feet per hour; the earth nineteen inches; Mars fifteen inches, Jupiter eight, Saturn six, Uranus four, and Neptune only about three and a half inches per hour. This latter planet would require 165 years to complete its circuit of New York.

Kepler discovered the three laws of planetary motion; Newton interpreted those laws and showed, with certain limitations, that they are the direct consequences of one fundamental law of nature: the law of

universal gravitation. In reaching this conception Newton was greatly aided by the physical researches of Galileo, who had developed the theory of falling bodies and laid the foundations of the modern science of mechanics. Near the surface of the earth bodies fall toward its centre with constantly increasing velocities, but in each second of time the velocity is increased, or accelerated, by the same amount; and this acceleration is the same for all bodies, whatever their nature. This acceleration is due to the attraction of the earth. Newton, noting that this attraction extended to all parts of the earth, to the highest mountains and to the adjacent air, was naturally led to infer its extension to the moon, and he made calculations which demonstrated that the force which retains the moon in her orbit is the same as that which causes bodies to fall upon the surface of the earth. He further showed that this force diminishes as the square of the distance from the earth's centre increases.

A simple calculation will show how this may be verified. In a sidereal month the moon travels once around the earth in her orbit. Her mean distance is 60.27 times the equatorial radius of the earth, and this radius is 20,926,000 feet in length. From these figures, upon the assumption that the orbit is a circle, may be found the entire number of feet travelled by the moon in one month of 27 days, 7 hours, 43 minutes, and 11 seconds. By dividing the entire circumference of the moon's orbit by the number

(2,360,591) of seconds in the month, it is readily found that the moon moves 3356.96 feet per second. If she were not subjected to the attraction of some external force, the moon would move in a straight line tangent to the actual orbit and at this constant speed, and would, therefore, each second move farther and farther away from the earth. As her orbit is a circle about the earth as centre, the moon must be deflected from her rectilinear path, or must fall toward the earth. The amount of this deflection, or fall, during each second can be calculated by simple geometry, and it is readily found that in each second the moon falls one twentieth (0.0536) of an inch toward the earth.

If now this deflection of the moon is caused by the attraction of the earth, and if this attraction varies as the inverse square of the distance, then at the surface of the earth a body should fall in one second a distance equal to one twentieth of an inch multiplied by the square of the moon's distance, expressed in radii of the earth. That is, a body should fall, $0.0536 \times (60.27)^2$ inches, or 16.2 feet. Experiments on falling bodies at the surface of the earth show that all such bodies actually fall in the first second through a distance of 16.1 feet; this quantity varying slightly, however, with the latitude of the place of observation. This quantity agrees so nearly with that derived from the rough calculation on the moon's orbit, that one is justified in concluding, as did Newton in 1686, that the force which retains the

moon in her orbit is the same force that causes bodies to fall to the earth.

The earth thus attracts the moon, and unless that attraction ceases at some point, the earth must also attract the sun, the planets, and all the bodies of the solar system. Reciprocally the sun must attract the earth, the moon, and each and every planet, and in turn the planets and satellites must attract the sun. Thus may be inferred the law of universal gravitation.

Every particle of matter attracts every other particle with a force proportional to the product of their masses and inversely as the square of their distance apart.

This law can be pretty clearly established for all bodies constituting the solar system; but it cannot be rigorously demonstrated for the universe at large. It is an empirical law; a law deduced from experience. As soon as formulated, however, it can be tested by applying it to the complicated motions of the bodies of the solar system. Ever since the time of Newton mathematicians have attempted to derive all these motions from this one comprehensive law. These attempts have been wonderfully successful; not only does the law explain the simpler movements of the planets, but the irregularities, the seeming inconsistencies in their motions, have one by one been shown to follow directly from this law. Further than this, from the assumption of the truth of this law a new planet was discovered: from the observed irregularities in the motion of Uranus, two mathema-

ticians, Le Verrier and Adams, independently predicted the finding of a new body and instructed the astronomers where to look for it.

The laws of Kepler are found to be but approximations. The planets do not describe ellipses around the sun, nor do they describe any simple geometric curves. The law of gravitation shows that, if the solar system consisted of two bodies only, the sun and a single planet, Mars for example, then would Kepler's laws be true and Mars would for ever move about the sun in an elliptic orbit, the radius vector sweeping out equal areas in equal intervals of time. The introduction of a third body into the system destroys at once this adjustment; the attraction of this second planet pulls Mars out of its orbit and causes it to describe a complicated wavy curve. Owing, however, to the small size of the planet as compared to the sun, it can only temporarily drag Mars from the elliptic path. After the lapse of some definite period Mars will return to its regular orbit, only to be again pulled and hauled, first by one planet, then by another. These interruptions, or disturbances, in the purely elliptic motion of a planet are called *Perturbations;* and these perturbations are all strictly periodic in character; increasing, decreasing, and vanishing in regularly recurring cycles.

Some of these perturbations run through their course in a few months, or a few years. These depend upon the relative positions of the various planets in their orbits, the times, for example, when two

planets are in line on the same side of the sun, or on opposite sides of the sun. These are known as the "Periodic Perturbations" and are comparatively small for all the planets, the asteroids excepted. In the case of Mercury these perturbations never amount to more than 15″; for the earth to about 1′, and for Jupiter and Saturn to about 28′ and 48′ respectively.

There are some perturbations which depend upon the relative positions of the orbits in space; the mutual inclination of two orbits, or the way their perihelia lie with reference to each other. The periods of these perturbations are extremely long, and are measured by thousands of years. For short intervals of a few years, or centuries, therefore, these perturbations seem to be uniformly progressive, and on this account they are termed "Secular." These secular terms, when first discovered, were thought to portend the ultimate destruction of the solar system as it now exists. But the mathematical researches of Laplace and Lagrange established their periodic character and proved that the mutual attraction of the planets could never destroy the system, nor radically change the character of the orbits of the larger planets. The solar system is a stable system, so far as it is acted upon solely by the mutual gravitation of its own members.

The final aim of the mathematician and astronomer is to discover whether or not gravitation is the sole force acting upon the planets, whether the simple law of Newton will explain all astronomical phenom-

ena. During the two centuries which have elapsed since Newton wrote the *Philosophiæ Naturalis Principia Mathematica,* instruments of research have been made more and more precise; new methods of measurement and observation have been discovered, and with these advances have come discoveries of new complications in the motions of the planets and their satellites. Many able geometers have investigated these complications and one by one these seeming irregularities have been explained, have been shown to be the direct result of the law of gravitation. But will this continue to be the case? may not new irregularities be discovered that the law of gravitation will not suffice to explain? may not the law be modified in some special case? may not other forces come into play? The mathematical astronomer of to-day seeks to answer such questions and to furnish formulas and methods for discussing each new complication as it arises.

Le Verrier discovered a slight irregularity in the motion of Mercury, which for over half a century has been a source of trouble to astronomers and has led Newcomb to question the exactitude of the law of gravitation. The perihelion of Mercury's orbit has a "secular perturbation," or regular forward movement, amounting to 579.″16 per century. Taking into account the disturbing action of all the known bodies in the solar system, Newcomb shows that the law of gravitation will account for only 537.″62; or the perihelion of Mercury moves forward

along the plane of the orbit by some 41.″54 per century in a manner that cannot be accounted for. In his *Astronomical Constants* Newcomb discusses many possible explanations of this anomalous motion, and after careful treatment discards them all as untenable. He shows that this motion cannot be due to erroneous determination of the masses of the various planets, nor to hitherto undiscovered planets. For a readjustment of the masses, or the introduction into the system of new bodies, sufficiently large to explain this discrepancy, will introduce serious discordances into the motions of the other planets. He seems to accept, as the most probable explanation, the hypothesis, first propounded by Hall, that the gravitation of the sun is not exactly as the inverse square, but that the exponent of the distance is

$$2.0000001574$$

instead of 2. He provisionally accepts this as a working theory and introduces it into the computation of his tables of planetary motion.

This is not the first time that the exactitude of the law of gravitation has been called into question. Time after time astronomers have found seeming irregularities in the planets' motions, which they could not explain by, nor deduce from, this law of Newton's. In every case, however, later investigations showed the fault to lie in the imperfections of their methods; their calculations, or their assumptions in regard to the number and size of the planets were in error, not the law of gravitation. A discrepancy of only 2′ be-

tween the observed and theoretical places of Uranus led to the discovery of Neptune, and possibly the minute discrepancy in the motions of Mercury may lead to important discoveries regarding the properties or distribution of matter in the neighbourhood of the sun.

CHAPTER VIII

THE INNER PLANETS—MERCURY AND VENUS

MERCURY, although a difficult object to observe, has been known from prehistoric times. It appears to oscillate back and forth on either side of the sun, and never departs more than 28° from that luminary. When at its greatest eastern elongation the planet is visible for a short time after sunset, appearing as a star of the first magnitude just above the western horizon; at the time of its western elongation it rises shortly before the sun and may be seen just above the eastern horizon. On account of the short duration of twilight in tropical countries, Mercury is much more easily seen in America and in Southern Europe than in England and the countries of the far north. Copernicus, living in a high latitude and under a cloudy sky, was able to catch an occasional glimpse of this planet, but never able to make a satisfactory observation.

The early astronomers failed to recognise the identity of the morning and evening stars and had separate names for them: the Egyptians called them Set and Horus, and the early Greeks, Apollo, the

morning, and Mercury, the evening star. By the time of Plato, however, it was known that these were one and the same body and the name of Mercury became permanently identified with it. As far back as 264 B.C. there are recorded observations of the position of this elusive planet.

Mercury is the nearest known planet to the sun, its mean distance being a little less than four tenths that of the earth. Its orbit however is very eccentric as compared to those of the other planets; the eccentricity, 0.205, being exceeded by that of but two or three of the asteroids. Thus while the semi-axis major of its orbit is about 36 million miles, the actual distance of the planet from the sun varies from 28.5 million at perihelion to 43.5 million miles at aphelion. Around this ellipse the planet travels at an average speed of 29 miles a second, taking 87.97 days to complete the circuit. This is the sidereal period or true Mercutian year. The synodic period, or time from conjunction to conjunction, is considerably longer, being 116 days.

The accompanying diagram represents the orbits of Mercury and the earth and shows the relative position of the two bodies at various times. The plane of Mercury's orbit is inclined some 7° to that of the earth, cutting the latter in the line of nodes. This inclination of Mercury's orbit is greater than that of any other planet, and is so large that Mercury may appear from the earth to be as far as 8° from the ecliptic. For this reason the zodiac was made 16°

wide. The ascending node, or point where Mercury passes from the south to the north side of the ecliptic, lies in longitude 46°. The line of apsides, or major axis of the orbit, lies in such a direction that the planet approaches the sun most closely in longitude 75°.

Now if the earth be at E and Mercury at M, the

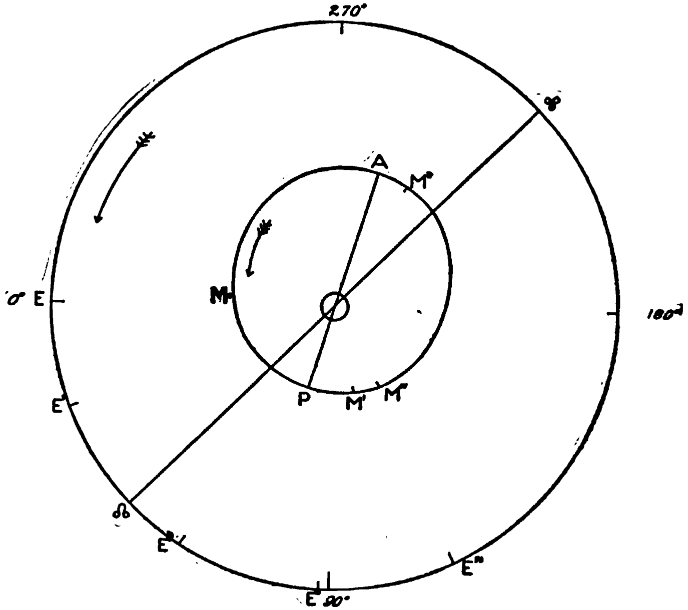


FIG. 20. ORBITS OF MERCURY AND THE EARTH.

planet will be in *inferior conjunction* and would appear slightly above the sun as a very thin crescent, somewhat like a new moon. Owing to the great brilliancy of the sun, however, the planet can never actually be seen when in this position. Mercury and the earth both move in the direction of the arrow and

about 22 days later will be in the positions M^{I} and E^{I} respectively, when the planet will appear at its greatest elongation and will be visible in the twilight. If viewed through a telescope the planet would now appear as a half moon. From this point on Mercury would appear to approach the sun until after some 36 days it would reach superior conjunction at M^{II}; during this time the planet would show the gibbous phase, appearing full at superior conjunction. When the planet reaches the starting-point, M, it has travelled once around its orbit and completed a sidereal period of 87.97 days. By this time the earth has moved on to E^{III}, and the planet will not catch up to it and be in inferior conjunction until the two bodies reach the respective positions M^{IV} and E^{IV} 116 days after starting out from M. Each successive inferior conjunction thus falls about 116° in advance of its predecessor, and there will be three such conjunctions each year, the third one occurring within a few degrees of the first.

Occasionally such a conjunction occurs when the planet is very near a node, and it will then appear to cross, or transit, the disc of the sun, appearing in a telescope as a small round black spot. The earth passes the line of nodes on May 7th and November 9th, and transits can therefore occur near those days only. The first transit ever observed was that of November 7, 1631, and the last that of November 14, 1907. As 3 synodic periods of the planet are equal to only 348 days and the year to 365, the third

successive conjunction will happen so far from the node that Mercury will pass either above or below the sun and no transit will occur. Twenty-two synodic periods however are equal to 2552 days, while 7 years equal 2556 days, and therefore after a lapse of 7 years a conjunction will occur within four degrees of the first, and a second transit may happen. Forty-one synodic periods differ still less from 13 years and 145 such periods differ from 46 years by less than a day. Thus transits at the same node may occur as frequently as 7 years and will almost certainly re-occur at intervals of 46 years. Transits are more frequent in November than in May, because in the former Mercury is much nearer the sun and will therefore appear against the disc when quite a distance to one side or the other of the node. During the next 25 years transits will occur as follows:

1914, November 7, visible in the United States.
1924, May 7, beginning only visible on Western Coast.
1927, November 9, invisible in the United States.

Although the transits of Mercury are of no great astronomical importance, they are observed with considerable interest and regularity. Observations of the planet's position on the solar disc at the times of transits have led, however, to one of the unsolved problems of mathematical astronomy. The perihelion is shifting its position in a way that cannot be accounted for and, as was noted in a former chapter, this has caused speculations as to the exactitude of the law of gravitation.

Owing to the revolution of Mercury about the sun its distance from the earth varies greatly. When an inferior conjunction occurs at aphelion the planet is only some 49 million miles distant, while at a superior conjunction it may be as far as 136 million miles away. The apparent diameter of the planet therefore varies in inverse ratio from 13″ to about 5″. Its real diameter is very close to 3000 miles, or a little more than one third that of the earth; its surface is about one seventh and its volume a little less than one eighteenth that of the earth. If the entire surface of the planet were spread out over the earth, it would cover Asia and Africa, and leave a little bit over to make some of the smaller islands in the Pacific.

The mass of the planet is not known with any great degree of accuracy. As Mercury has no satellite its mass can be determined only by the disturbing effect of the planet upon other bodies. One or two comets have passed near Mercury and that planet has caused slight variations in their motions. From such observations, Encke, von Asten, and Backlund have attempted to compute the value of the mass. Their estimates range all the way from one eighth to one fifteenth that of the earth. The most reliable determination is that of Newcomb in his *Astronomical Constants,* which was obtained from an elaborate discussion of the motions and orbits of the four inner planets. He concludes that the mass of Mercury is $\frac{1}{6,000,000}$ that of the sun, or about $\frac{1}{18}$ that of the earth.

This value is approximate only and according to Newcomb is almost certainly too large.

This uncertainty in the mass of the planet causes similar discrepancies to appear in estimates of its average density. Until Newcomb showed that its mass was much smaller than had been supposed, its density was thought to be as great as $2\frac{1}{2}$ times that of the earth, twelve times that of water, or approximately that of lead. It is now known that its density is very nearly the same as that of the earth, and that in this regard Mercury does not differ radically from the other terrestrial planets, Venus, the Earth, and Mars.

Telescopic observations of the surface of the planet are attended with considerable difficulty. Mercury is never visible at night; it must either be studied in full daylight, or in the twilight just before sunrise or after sunset. In the former case it may be observed on or near the meridian, but the heat of the sun disturbs the atmosphere and makes "good seeing" extremely rare. In the latter case the planet is seen near the horizon and the atmospheric disturbances are again very troublesome.

Schröter was the first to make any serious attempt to study the surface conditions of this planet. He noted that the edge of the terminator (the line separating the light and dark portions of the disc) appeared irregular, and thought this indicated the presence of a high mountain near the southern edge of the disc. From repeated observations he inferred the rotation of the planet on an axis in twenty-four

hours and five minutes. These results have never been satisfactorily confirmed, although Zöllner in 1874 reported the surface to be rugged and mountainous, and compared the appearance of the planet to that of the moon.

In 1882 Schiaparelli at the Milan Observatory noted many markings, from a careful study of which he concluded that Mercury rotates on its axis once in eighty-eight days. If this be true, Mercury revolves about the sun in a manner similar to that in which the moon revolves about the earth. The planet always presents the same face toward the sun, and on that side reigns perpetual day, on the other side perpetual night. Such a rotation is not at all improbable and is in full accord with the theories of tidal evolution. When Mercury was in a semi-fluid condition the action of the sun raised large tides and tidal friction would tend to increase the length of the Mercutian day and to make the periods of rotation and revolution identical. In 1896 Lowell seemingly confirmed Schiaparelli's ideas as to the period of rotation, but the observations are so difficult that the matter can hardly be considered as definitely determined.

Practically nothing definite is known as to the surface conditions existing on Mercury. The planet shows no definite well recognised markings, yet it is generally conceded that its surface is probably rough and irregular, somewhat resembling the moon in general characteristics. At Flagstaff, however, Lowell

and his assistants have made elaborate drawings, showing the surface crossed and recrossed with broken and irregular lines, resembling in a striking way the early drawings of the so-called "Canali" on Mars. These lines have not been seen by other observers and their existence is very doubtful. Lowell himself calls them "cracks."

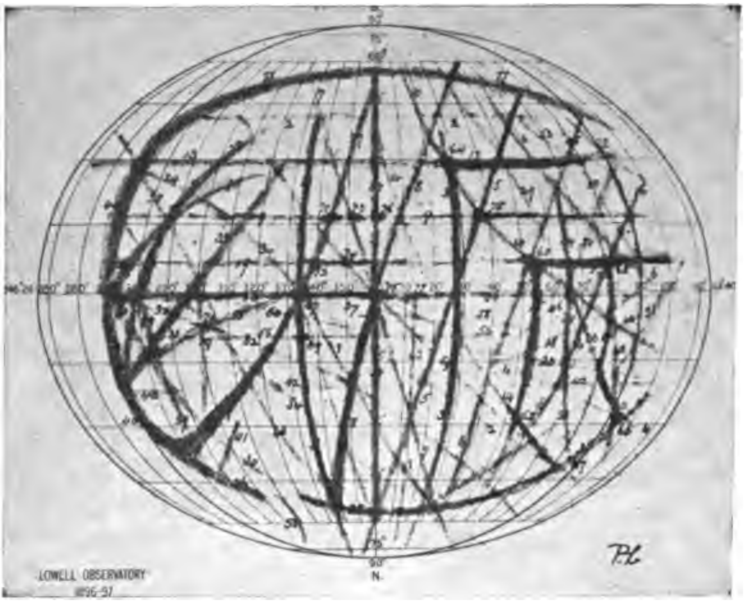


FIG. 21 CHART OF MERCURY AS DRAWN AT THE LOWELL OBSERVATORY.

Mercury has little or no atmosphere, and in this regard also closely resembles the moon. Many years ago Huggins and Vogel thought they had detected spectroscopic evidence of the existence of an atmosphere similar to that of the earth and containing water

vapour. Schiaparelli also speaks of Mercury as having "a moderately dense atmosphere." But later observations tend to disprove these ideas and to show that the atmosphere must be extremely rare. Lowell finds no evidence of clouds or atmosphere and the prevailing opinion now supports this view.

If these views in regard to atmosphere and rotation are correct, then the conditions on the planet must be extremely peculiar. The side turned toward the sun will be constantly exposed to the fierce rays of that body, shining with nearly seven times the power they do at the earth. Unprotected by any atmosphere the surface must be baked as in an oven. The other side of the planet is exposed, without a sheltering blanket, to the intense cold of inter-planetary space; here would reign perpetual night and unbroken, unimaginable cold.

The peculiar motion of the perihelion of Mercury's orbit, mentioned in a former paragraph, was discovered by Le Verrier in 1845 and by him explained as due to the attraction of a planet, or planets, travelling about the sun within the orbit of Mercury. Such a planet was supposed to have been discovered by a physician and amateur astronomer, Lescarbault, in 1859 and was named "Vulcan." It was described as having an apparent diameter of about 7″ and according to Le Verrier's computations was about 13,000,000 miles from the sun and revolved about that body in between 19 and 20 days. Although never again seen, Vulcan was recognised for a number of

years as a permanent member of the solar system. Yet it is now practically certain that Vulcan does not and never did exist.

Total solar eclipses offer the best opportunities for detecting faint bodies near the sun. A planet large enough to have been seen with the little telescope of Lescarbault should be a rather conspicuous object at the time of its elongation and should certainly be visible when the direct light of the sun is cut off by the moon. For many years every opportunity has been utilised and careful searches have been made, but no planet has ever been discovered. In 1878, while observing the eclipse of that year, Watson detected two planet-like objects near the sun and for awhile belief in the existence of Vulcan was revived. But later investigations showed conclusively that Watson had seen, not planets, but two well-known fixed stars. During later years many photographs have been taken at times of solar eclipse, some with the especial purpose of detecting any unknown planets. In 1901 Perrine obtained photographs which showed the presence, in the immediate vicinity of the sun, of more than fifty stars, ranging upward in brightness from the eighth magnitude. All of these bodies were identified with known fixed stars. From all such observations and photographs the conclusion seems inevitable that there can be no intra-mercurial planet large enough to appear as bright as an eighth magnitude star. And such a planet would be many thousand times smaller than the supposed "Vulcan."

Venus. Of all the larger planets Venus approaches the earth most nearly, and is the most brilliant object in the heavens, the sun and moon alone excepted. Like Mercury it oscillates backward and forward, appearing first to the eastward and then to the westward of the sun, but never departing more than 47° from that luminary. When to the eastward of the sun it may be seen in the western sky, shining brilliantly for a few hours after sunset; when west of the sun it rises before dawn and outrivals all the stars of the eastern sky. The ancient astronomers did not recognise the identity of the morning and evening stars and named them Phosphorus and Hesperus respectively.

The orbit of Venus is very nearly circular, the eccentricity, 0.0068, being the smallest in the solar system. In size it is about 0.72 that of the earth, the mean distance of the planet from the sun being approximately 67,200,000 miles. At inferior conjunction Venus approaches the earth to within 26 million miles, and then appears as a thin crescent nearly 67″ in diameter. At superior conjunction its distance is over 160 million miles and then Venus appears as a round disc some 10″ or 11″ in diameter. The planet thus varies greatly in apparent size and in brightness. While it reaches its greatest apparent diameter at inferior conjunction, yet at that time it shows such a thin illuminated crescent that it is not so brilliant as it becomes later when more of the illuminated surface is turned toward us. In fact the planet reaches its

greatest brilliancy some thirty-six days before and after inferior conjunction. At these times the crescent widens out, until the planet appears like the moon five days old. It is then so bright that it may easily be seen in the daytime and on a clear, dark night it casts a distinct shadow.

Like Mercury, Venus exhibits all the phases of the moon. This was one of Galileo's first telescopic discoveries, and was used by him as a strong argument for the truth of the Copernican theory of the solar system. In order to prevent any one from claiming priority in this discovery, he published in 1610 the following anagram:

"Hæc immatura a me jam frustra leguntur; O. Y."

Subsequently he announced his discovery and rearranged the letters in the above words so as to make a complete sentence, which when translated into English would read:

The mother of the loves [Venus] emulates the phases of Cynthia [the moon].

These phases are repeated every 584 days, which is thus the synodic period of the planet; a little less than one year and four months. The corresponding sidereal period, or true year of the planet, is 224.7 days, or it takes Venus only about six tenths as long to travel its orbit as it does the earth.

The inclination of Venus's orbit to that of the earth is small, only about $3\frac{1}{2}°$, and the earth passes the nodes on June 5th and December 7th. At these

times if Venus be in inferior conjunction, the planet will appear to "transit" across the disc of the sun, and such transits have been extensively observed in the hope of obtaining a reliable value of the solar parallax. These transits are extremely rare phenomena, but five having ever been observed. The first

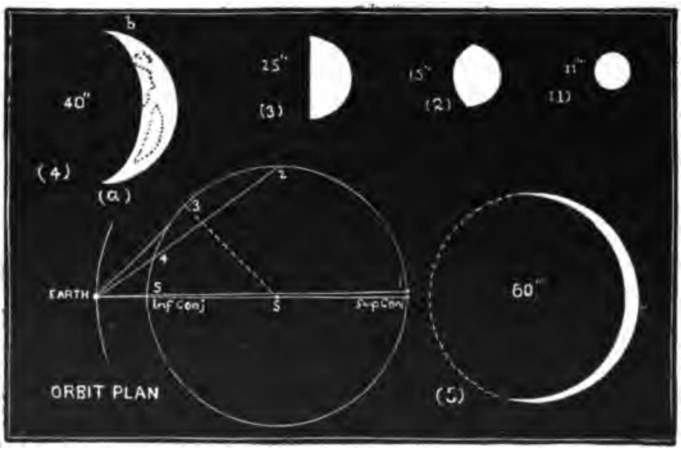


FIG. 22. THE PHASES OF VENUS FROM YOUNG'S "GENERAL ASTRONOMY."

was seen by only two persons—Horrox and Crabtree—on December 4, 1639; the last, in 1882, was observed by many; costly expeditions were fitted out and elaborate preparations made by the whole scientific world. These observations failed of their main purpose,[1] but proved of great value for determining the motions of Venus.

Thirteen revolutions of Venus about the sun require 2921.1 days, while in 8 sidereal years there

[1] Compare Chapter IV., "The Distance of the Sun."

are 2922.0 days. Thus every 8 years the earth and Venus return to almost the same relative positions in the heavens, and if a conjunction occur exactly at the node, then the conjunction will be repeated 8 years later within a degree of the node. Venus, however, is so near the earth that such a conjunction must happen almost exactly at the node in order that there be a transit; otherwise Venus passes above or below the sun's disc. If then a transit occur at any time, there may be another at the same node at the lapse of 8 years. After 16 years, the conjunction would occur too far away from the node for a transit to take place. Each successive period of 8 years will bring the conjunction farther and farther away from the node and not until 243 years have passed will a conjunction again happen at that node. In about one half this period, however, a conjunction may occur sufficiently near the opposite node for a transit to be seen. The transits at present happen in pairs at each node, the members of each pair separated by 8 years, and the pairs separated by intervals of about 121 years. The dates of recent and future pairs are:

1631, December 7.	1874, December 9.
1639, December 4.	1882, December 6.
1761, June 5.	2004, June 8.
1769, June 3.	2012, June 6.

The transit of 1631 was not observed. It will be noted that during the present century there will be no transit, and therefore no one now living can hope to again witness this phenomenon.

The real diameter of Venus is now known to be about 7826 miles, with an uncertainty of less than 30 miles. Thus this planet is almost a counterpart of the earth in size, its surface being nearly ninety-five per cent. and its volume ninety-two per cent. that of the earth. Newcomb, in his classic work, finds that the mass of the body is but $\frac{1}{408,000}$ that of the sun, or about eighty per cent. of that of the earth. The average density of Venus is, therefore, slightly less than that of our own planet. But, on the whole, so far as their general characteristics are considered, Venus is a twin sister of the earth.

Although Venus is our nearest neighbour, yet practically nothing is known of the conditions existing on the planet's surface. This is due to the dense atmosphere which surrounds the planet and veils her mysteries from our gaze. Schröter in 1792 noted the diminution in brilliancy of the disc near the terminator, saw the horns of the crescent extend far beyond a semicircle, and explained this appearance as due to the presence of an atmosphere. This view has been repeatedly confirmed and it is now well established that the atmosphere of Venus is more dense than that of the earth. To the effects of the dense atmosphere may be attributed the failure of the transit observations to successfully solve the problem of the solar parallax. As the planet entered upon the disc of the sun, it appeared surrounded by a luminous ring, due to refraction and reflection from the clouds and vapours floating in its atmosphere. By

this the observed times of contact were rendered uncertain by several seconds and the observations marred and distorted and rendered of little real value.

Some evidence of the presence of water vapour has been adduced. Tacchini and Young both noted that the bands in the spectrum due to water vapour were considerably enhanced in the spectrum of Venus. Janssen, observing with more powerful instruments, found only slight traces of water, while Vögel could hardly detect the slightest variation from the solar spectrum. The light which reaches our instruments is probably reflected from the upper surface of vast banks of cloud and really penetrates the atmosphere of Venus but a short distance.

No well-defined surface markings are visible, yet as early as 1643 Fontana called attention to certain irregular appearances along the inner edge of the crescent. Schröter repeated Fontana's observations and detected irregularities along the terminator, larger and more marked than those in the moon. He considered this proof of the presence of high mountain ranges and estimated the height of some of those near the southern horn of the crescent to be at least twenty-seven miles. Similar observations have been made in later years by Mädler, De Vico, and others. Herschel and other observers have failed to confirm these appearances, and it would seem as if the evidence pro or con is entirely insufficient to warrant any definite conclusion. Many of the earlier obser-

vations were undoubtedly due to cloud forms in the dense atmosphere.

As early as 1666 the elder Cassini thought that he had detected a rotation of the planet in a little more than twenty-three hours. But Bianchini a few years later, as the result of an extended series of observations, came to the conclusion that Venus rotates very slowly and that her day is equal to more than twenty-four of our days. Still later Schröter, after nine years of patient watching, noted a mark near the southern horn which apparently appeared and disappeared in a regularly recurring period. As noted in the preceding paragraph he ascribed this to the presence of a high mountain, and determined from it the period of rotation of the planet as twenty-three hours and twenty-eight minutes. During the years previous to 1841, De Vico at Rome made over ten thousand observations of the planet and practically confirmed the rotation period of Schröter. As a result of his most elaborate investigation he concluded that Venus rotates about an axis inclined 53° to her orbit in a period of twenty-three hours and twenty-one minutes. For many years this result was very generally accepted, although some astronomers considered the proof as inadequate.

In 1890 Schiaparelli reopened the discussion. He fixed his attention on certain bright spots near the southern horn and watched them for many consecutive hours. To do this he was obliged to observe during the daytime, and early evening. He found that

these spots never changed their positions relative to the terminator; that during a day's observation the line separating day from night on Venus does not shift to any appreciable extent over the surface of that planet. The theory of a rapid rotation seemed to be excluded and Schiaparelli concluded that Venus

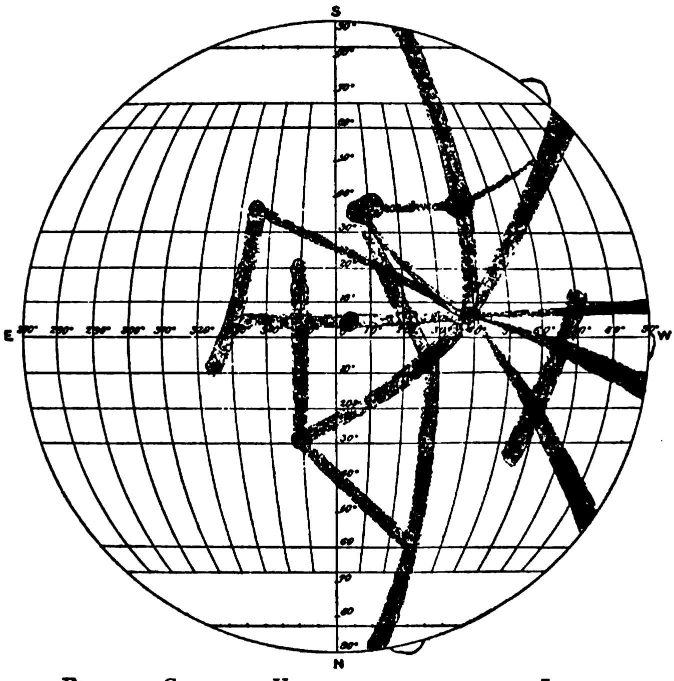


FIG. 23. CHART OF VENUS AS DRAWN AT THE LOWELL OBSERVATORY.

rotates like Mercury and the moon, always presenting the same face to the sun. The period of rotation of the planet would thus be 224 days, the same as the

sidereal period. This surprising and most remarkable result was confirmed in 1895–96 by Perrotin at Nice and later by Lowell in Arizona. Tacchini, Mascari, and Cerulli have also repeated the observations and reached the same conclusion as did the distinguished Italian.

On the other hand many observers disagree with this result. Trouvelot, Williams, and Brenner agree more nearly with the earlier observations of Schröter and make the period approximately twenty-four hours long. The spectroscope has been called upon to decide the question and Bélopolsky has obtained spectrograms which indicate a rapid rotation. The observations, however, were admittedly tentative, and too much weight must not be placed upon them. Thus the question of the rotation of Venus is still an open one; her day may be similar in length to our own or perpetual day may reign in one portion of the surface and perpetual night on the other. If the spectroscopic observation be confirmed, then all past observers have mistaken cloud forms for permanent features of the surface.

The drawings of the planet obtained by Lowell at Flagstaff are remarkable. They show the surface crossed by broad dark bands, which radiate from distinct centres. These markings, according to their discoverer, are permanent features of the planet, are perfectly distinct and invariably visible; nothing but unsteady air can obliterate them, and at times their contours have the "look of a steel engraving." These

markings appear of a straw-grey colour against a brilliant uniform straw coloured surface and seem to be "barren rock or sand weathered by means of exposure to the sun." It was from these markings that Lowell confirmed Schiaparelli's theory in regard to the rotation period of the veiled planet. The reality of these dark bands has not been confirmed by independent observations, and in view of the similar appearances noted by Lowell on Mercury and on Mars their actual existence is rendered extremely problematical. This subject is referred to more fully in the chapter on Mars.

If the three mountains, indicated on the chart, be drawn to scale, they represent astounding elevations, the higher one being fully 240 miles high.

CHAPTER IX

MARS

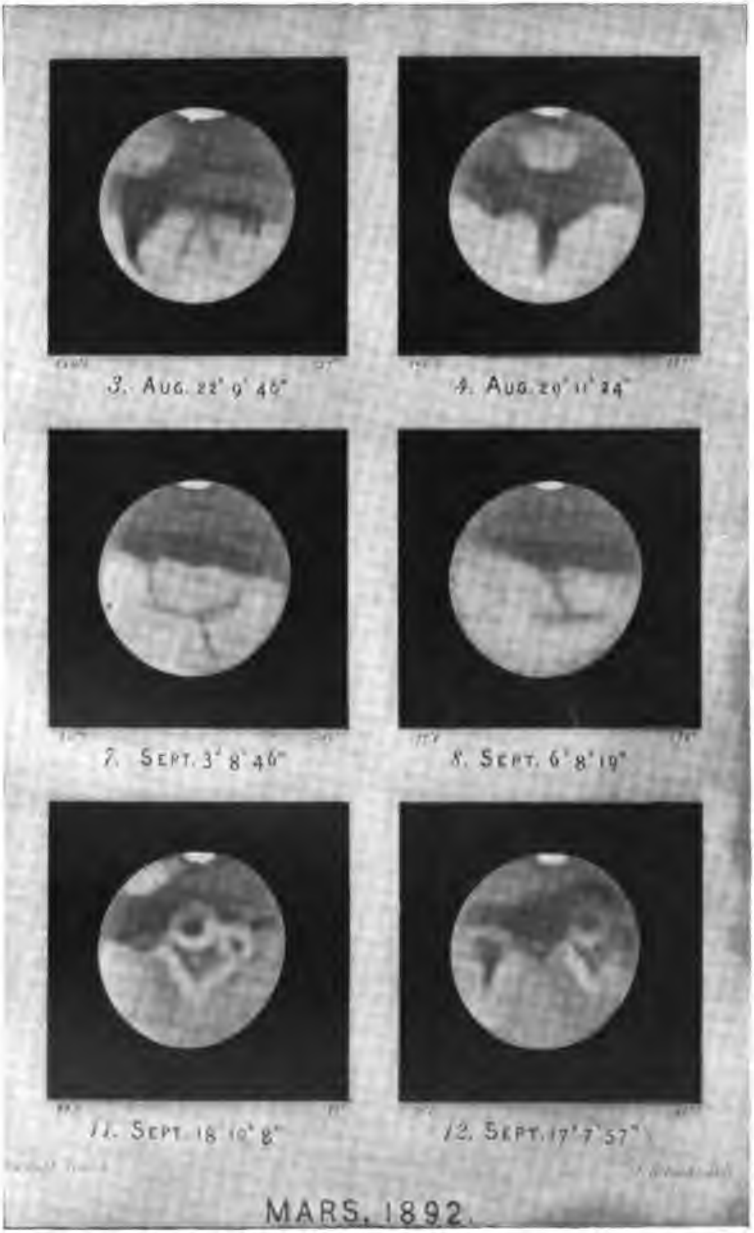
MARS has been known from prehistoric times. Its brightness, its brilliant ruddy colour, the extent and eccentricity of its motions among the stars, all tend to make it one of the most prominent objects in the heavens. It has always been watched and studied with the utmost care and attention. Aristotle noted an occultation of this planet by the moon, and inferred therefrom the greater distance of the bloody star. From the observations of Tycho Brahé upon the positions of the planet Kepler found its true orbit, deduced his celebrated laws of motion, and made the first grand step in our knowledge of the mechanical construction of the solar system.

Among the early astronomers rapidity of motion was the only criterion of distance. Mars completes a circuit of the heavens in about two years, and hence in the system of Ptolemy this planet was placed at a greater distance from the earth than the sun. Copernicus gave to the world the true conception of the solar system and estimated very closely the proportionate distance of Mars from the sun. He showed

that Mars is about $1\frac{1}{2}$ times as far from the sun as is the earth, but this latter distance he knew only very inaccurately. He showed that the distance of Mars from the earth varied enormously and that the apparently capricious changes in brilliancy were coincident with these variations in distance.

Mars revolves around the sun in an ellipse, the semi-axis of which is 1.52 times that of the earth's orbit, or 141,500,000 miles. The eccentricity of the orbit is 0.093, so that the sun is some 13,000,000 miles from the centre of the curve, and the actual distance of Mars from that central luminary varies between 128 and 154 million of miles. The earth takes $365\frac{1}{4}$ days to travel once around its orbit, Mars requires 687 days, or 1.88 years, to complete its path.

When Mars is in the corresponding part if its orbit as the earth, the planet appears directly opposite the sun, and is said to be in *opposition*. At these times Mars is on the meridian at midnight and is, therefore, in the most favourable situation for observation. The time from one opposition to the next is called the synodic period, and this period is longer than the true orbital or sidereal period of 687 days. Starting from corresponding parts of their respective orbits the earth and Mars move around the sun in the same direction, the earth moving the faster of the two and dropping Mars farther and farther behind. When the earth has completed one revolution and returned to the starting point, Mars will have covered $\frac{6}{11}$ of its orbit and will be just approaching superior con-



Mars in 1892 from Drawings Made by James E. Keeler

junction. From this point on the earth gains on Mars, but not until Mars has completed more than one circuit of the heavens does the earth overtake it and the second opposition occur. The synodic period is thus 780 days, or 2 years and 50 days, the longest in the planetary system. Successive oppositions occur thus at different portions of the planet's orbit, and on account of its eccentricity the distance between Mars and the earth, at these times, varies widely. At the average opposition Mars approaches the earth to within 48,600,000 miles. If an opposition happen when Mars is near perihelion this distance is reduced to 35,000,000; but if the opposition occur at aphelion the average distance is increased to 61,000,000 miles.

The apparent diameter of the planet as viewed from the earth varies inversely as the distance. The nearer the planet is to the earth the larger it appears. Hence at an opposition near perihelion the disc will appear nearly twice as large as at an opposition near aphelion, and nearly eight times as large as when the planet is in conjunction. The brightness of the planet varies very nearly as the squares of these numbers; so that at a favourable opposition Mars is nearly four times as bright as at an unfavourable one, and some fifty-three times brighter than when in conjunction. When near conjunction, Mars is a very inconspicuous morning or evening star, being possibly a little brighter than the pole-star; in a favourable opposition, on the other hand, Mars shines forth in

the midnight sky, far more brilliantly than any of the fixed stars.

These great changes in the apparent disc of the planet are shown in the annexed figure, which shows the planet in various relative positions of its orbit drawn to a scale of 20″ to one inch. At a favourable opposition the planet appears 24″.8 in diameter, at conjunction 3″.6. That is, under the most favourable circumstances, Mars appears as large as would a silver twenty-five cent piece at a distance of six hundred and fifty (650) feet.

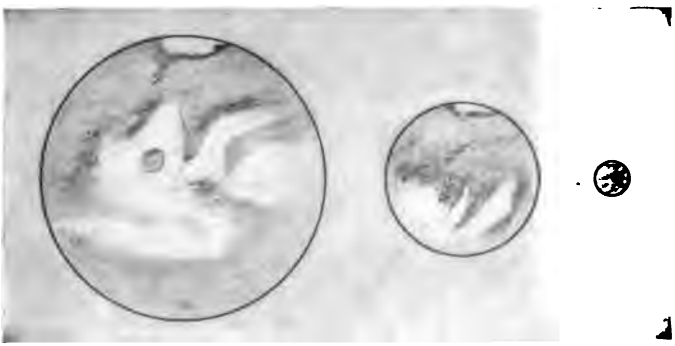


FIG. 24. APPARENT SIZE OF MARS AT VARYING DISTANCES.

These favourable oppositions occur at alternate intervals of fifteen and seventeen years. As the average synodic period is some two years and fifty days long, each successive opposition will fall about 50° or one seventh of the circumference in advance of the preceding one. Thus the seventh opposition will occur very nearly in the same part of the orbit as the

first, and seven oppositions require within a few days of fifteen years. In fact in seven synodic periods there are 5460 days, while in eight complete revolutions of the planet there are 5496 days, or the seventh opposition will occur thirty days before the planet arrives at that part of its orbit in which the first happened. The fifteenth opposition falls still more closely upon the same part of the orbit as the first, occurring only twenty-one days after the planet has passed the point at which the first occurred. The last perihelion opposition occurred in 1892, the next will come in 1909, although that of 1907 will be very nearly as favourable. The following table shows the distance and apparent diameter of the planet at the various oppositions during the last cycle from 1892.

Date	Distance	Diameter
1892, August 4–6,	0.37736	24.″8
1894, October 12–14,	0.43100	21.″7
1896, December 6–7,	0.56110	16.″7
1899, January 15,	0.65097	14.″4
1901, February 22,	0.67740	13.″8
1903, April 3,	0.63810	14.″7
1905, May 16,	0.53660	17.″4
1907, July 13,	0.40760	22.″9
1909, September 24,	0.39191	23.″9

The orbit of Mars lies in a plane inclined but 1° 15′ to the plane of the ecliptic. The ascending node is in longitude 48°, while the perihelion is in 333°. Hence near perihelion Mars will always be south of the ecliptic, and near aphelion north. The earth passes the line of apsides in longitude 333° on or about

August 27th of each year, so that the most favourable oppositions always occur late in August or in September.

The first recorded telescopic observations of Mars were those made by Galileo. By December, 1610, he had noted that the planet's disc was not perfectly round, and that it exhibited phases similar to the gibbous phases of the moon. As the orbit of the earth is wholly inside that of Mars, this latter planet can never pass between the earth and the sun, and, therefore, can never appear as a crescent. At opposition and at conjunction the visible disc is fully illuminated, at quadrature a portion of the illuminated disc is turned away from the earth, so that the planet appears decidedly gibbous. But the unilluminated zone never exceeds one seventh of the entire disc; Mars appearing, under these circumstances, somewhat like the moon two or three days before or after the full. The phase is a little more marked than this when quadrature occurs near perihelion, a little less marked when the planet is near aphelion.

The earliest drawings of the planet's surface were made by Fontana in 1636, and these drawings are still extant. They show the bright disc marred by a central dark spot and by a dark ring near the edge. Fontana described the disc as showing several colours, and the planet as being brighter than any of the heavenly bodies, the sun alone excepted. Unfortunately, however, nearly all these markings of Fontana can now be shown to be optical illusions, to be due to de-

fects in his puny telescope. The first reliable sketches were made by Huyghens in 1659, when he noted certain characteristic markings, which can be recognised to-day and identified with certain permanent features of the planet. While watching these spots, he noted their movement across the disc of the planet and inferred a rotation of Mars, similar to that of the earth, in twenty-four (24) hours. A few years later, in 1666, Cassini made much more elaborate drawings and determined the period of rotation to be 24 hours and 40 minutes.

These early drawings are of great value to-day, as they enable us to make a most accurate determination of the rotation period of the planet. From modern observations, extending over a few days or weeks, the length of the Martian day can be found to within a second or two. With this approximate period, the whole number of rotations between any two observations, or drawings, can readily be calculated, no matter how many years may separate them. A comparison of the modern and ancient drawings will furnish the outstanding fractional part of a revolution, and thus the period of rotation be fixed with great precision. In this way Proctor, Kaiser, Bakhuyzen, and others have determined this period. Of all these modern values that of Proctor, 24h. 37m. 22.71s., is the largest, that of Schmidt, 24h. 37m. 22.60s., the smallest. These two determinations differ by only 0.1s; the mean of a number of the best modern values is given by Flammarion as 24h. 37m. 22.65s

and this is probably correct to within a part of a second.

This is the sidereal rotation of Mars, corresponding to the sidereal day on the earth. Now a Martian year is 686.98 of our mean solar days long, and each Martian sidereal day is, as above, 1.026 days long. Hence a Martian year consists of 669.6 Martian sidereal days. And as in each year the number of sidereal days exceeds the number of solar days by one, there will be 668.6 Martian solar days in a Martian year. Therefore 686.98 of our mean solar days exactly equal 668.6 Martian solar days, or each Martian solar day is 24h. 39m. 35s. long.

The axis about which Mars rotates is inclined 24° 50′ to the plane of the orbit, and therefore the seasonal changes (so far as they depend upon this) on Mars should correspond very closely to those on the earth. The surface of the planet is divided into torrid, temperate, and frigid zones. Every place situated within 24° 50′ of the equator will have the sun directly overhead on two days of the year; every place within 24° 50′ of either pole will have days when the sun remains constantly above the horizon, and periods when the sun never rises. The plane of Mars' equator cuts the plane of the orbit in a line directed toward longitude 87°, and this point of the Martian heavens corresponds to our Vernal Equinox. When Mars reaches this point of its orbit, the sun will be on the equator and it will be the beginning of spring in the northern hemisphere. When the planet reaches

longitude 177° the north pole will be turned toward the sun, and it will be the middle of summer in the northern and the middle of winter in the southern hemisphere. These seasons on Mars are nearly twice as long as ours, summer in the northern hemisphere lasting 381 days and winter only 306. At the north pole the night is 306 days long, then for 381 days the sun never sets. In the southern hemisphere the winter is longer than summer, the night at the south pole being 381 days and the day 306 days long.

These seasonal changes do not necessarily indicate radical climatic differences such as exist on the earth. The planet is so far from the sun that the amount of heat and light received is much less than received by the earth. The mean apparent diameter of the sun as seen from Mars is only 21′ 2″, about two thirds that as seen from the earth; and the amount of heat received from the sun is only about four tenths that which we receive. Again the physical conditions of the planet itself, the density and constitution of its atmosphere, will modify tremendously any conclusions that might be drawn from the seasonal effects only.

The first reliable measures of the size and shape of Mars were those made by Sir William Herschel in 1784, who found the apparent diameter of the planet at distance unity to be 9.″13. He also noted a flattening at the poles similar to the known ellipticity of the earth. According to him, however, this polar compression was much greater than that of our planet,

being nearly $\frac{1}{16}$. Modern observations make the diameter somewhat greater, Le Verrier placing the equatorial diameter at 11.″1, others making it as low as 9.″2. The measures are rather discordant, but with the exception of that of Le Verrier, which is manifestly too high, they all range around 9.″35. With a solar parallax of 8.″80, this would make the real diameter of Mars 4210 miles. An error of one tenth of a second of arc in the measured diameter is equivalent to an error of 45 miles in the real diameter of the planet. As the error, if any, can hardly be as large as this, the size of Mars is known with extreme accuracy.

The surface of the planet is very nearly 0.28, or a little less than one third, that of the earth. This is but a trifle more than the total area of dry land upon the earth; in other words, if on our globe the oceans and seas were eliminated and the continents fitted together, the result would be a globe only a little smaller than Mars. The volume of such a globe is 0.149, or about one seventh that of the earth.

The mass of the planet can be determined with great accuracy from observations of the satellites, discovered by Hall in 1877. Newcomb, in adopting the Hall value, shows that it cannot be in error by so much as two per cent. and that this degree of precision is much higher than could be obtained by any other method. According to Hall the mass of Mars is 0.105 that of the earth, or a little less than one three millionth that of the sun. As its volume is one

seventh, while its mass is only one tenth that of the earth, its average density must be slightly smaller than that of our planet, being in fact about seven tenths as great, or about four times that of water.

The weight of a body at the surface of a planet depends upon the attraction of gravitation, and this increases with the mass and decreases with the square of the diameter of the planet. As Mars contains only one tenth as much matter as the earth, its attraction at equal distances will be only one tenth as great, but, on the other hand, the surface of Mars is only one half as far from the centre as is the earth's surface, and, on this account, the attraction will be quadrupled. Thus the surface gravity of Mars will be about four tenths (0.38) that of the earth. If a man of the average weight of 150 pounds could be transported to Mars, he would there weigh 60 pounds only. If he retained his muscular strength, his activity would be wonderfully increased, he could run faster and jump farther.

The study of the physical characteristics of the planet's surface began in 1784 with Sir William Herschel's explanation of the "polar caps." These brilliant white spots which cap each pole had been seen and sketched by Cassini nearly a hundred years previously, but he had not recognised their true nature and significance. In the great reflecting telescopes constructed by Herschel, the planet was seen as never before and during the oppositions of 1781 and 1783 the polar caps were seen and studied on many even-

ings. They were generally circular in shape, their centres being near, but not at the poles; and they appeared to alter in size. In 1781 the southern cap was perfectly round and quite extensive, stretching 20° to 25° on every side of the pole and covering the entire polar regions above Martian latitude 65°. By 1783 it had dwindled to a mere spot, barely covering the pole. It was not quite symmetrically placed, however; the pole being within the spot, but not at the centre. As the planet rotated each day, the spot appeared to describe a minute circle upon the disc. These changes in the size of the spot were found by Herschel to depend upon the Martian seasons. During the months of the long polar night, the spot increased in size, only to diminish during the alternate period when continuously exposed to the direct rays of the sun. Similar phenomena occur on the earth; every winter vast fields of ice are formed and snow is deposited over great areas in the northern hemisphere, thus forming a brilliant white cap around the north pole. Every summer much of this snow and ice melts and the cap dwindles in size. Reasoning from this analogy Herschel concluded that the brilliant spots visible on Mars are due to the formation of real snow and ice during the Martian winter, and that their diminution is due to the melting of this snow and ice during the long days of summer.

The polar caps of Mars and the changes they undergo are illustrated in a series of beautiful drawings made by Keeler at Allegheny during the opposition

of 1892. The first drawing shows Mars as it appeared on August 22d, the last as on September 18th. During this interval of twenty-seven days, the cap shrank appreciably, diminishing to about one half the size shown in the first drawing.

Herschel's explanation of the polar caps, as true ice caps, implies the existence of an atmosphere surrounding and enveloping the planet, an atmosphere in which the vapour of water is carried from the warm regions of the equator and deposited in the form of snow at the poles. That Mars is surrounded by an atmosphere there is an abundance of proof, but that the atmosphere is similar to that of the earth is not so well established. The existence and behaviour of the polar caps proves without question the presence of an atmosphere consisting of some sort of vapours which are condensed and precipitated by cold. This atmosphere is, however, extremely rare and transparent, and offers little or no obstruction to the detailed study of the planet's surface. Clouds, if any exist, are very infrequent, very thin, and semi-transparent. No great opaque masses of vapour, similar to terrestrial storm clouds, have ever been noted. Certain observers have reported, however, at times the presence of a very thin haze, half veiling the surface markings. This haze appears over the cooler portions of the planet's surface, especially over portions of that hemisphere in which it is winter, seldom over the equator. As a whole the atmosphere is remarkably clear and transparent.

Many attempts have been made to prove by means of the spectroscope the presence of water vapour in the Martian atmosphere. The light which we receive from Mars is sunlight, reflected from the surface of the planet and which has, therefore, passed twice through the Martian atmosphere. Vapours in that atmosphere will absorb their own characteristic rays, or wave-lengths, of light, and make their presence known by modifying the solar spectrum. In the early days of spectrum analysis Huggins and Vogel established, as they thought without doubt, the presence of water vapour in the Martian atmosphere. As a result of his researches in 1872 and '73, Vogel wrote: "We may conclude with certainty that Mars possesses an atmosphere, which in composition does not differ essentially from our own and which is particularly rich in the vapour of water." But vapours in our own atmosphere similarly cause absorption bands and make it extremely difficult to determine with certainty whether an observed effect is due to the Martian atmosphere or to our own. And recent investigations indicate that Vogel's conclusions were too hastily drawn and were of too sweeping a character. Observations carried out at the Lick Observatory, with the most powerful instruments and under the most favourable atmospheric conditions, do not show any indication of water vapour on Mars. The theoretical researches of Jewell in Baltimore show that the largest instrument yet constructed is not delicate enough for these observations, that it is

useless to attempt to prove by the spectroscope the presence or non-presence of water vapour in the Martian atmosphere. Spectrum analysis thus fails to establish anything definite in regard to the atmospheric conditions on Mars.

In addition to the polar caps, the surface of Mars presents many striking and permanent features. Under ordinary conditions of seeing, the disc appears a deep ruddy colour, and against this orange background darker, grey-green spots and markings are seen. Fontana recorded his impression of varying colours and Huyghens left sketches which distinctly show the broader features of the planet's markings. But it was not until the middle of the last century that these surface markings were carefully studied and charted, and complete maps of the planet drawn. Beer and Maedler executed the first Martian survey and published their map in 1840. This was made on Mercator's projection and showed the larger markings only. Subsequent maps show more and more detail; each observer saw what his predecessor had seen and something more, thus adding his mite to the geography of Mars. Following the lead of Herschel the lighter portions of the surface were thought to be continents and islands, the darker portions seas and oceans. Names were assigned to the more prominent features and the Martian maps of forty years ago were as complete and full as were the maps and charts of our own world.

Schiaparelli was the first to doubt this orthodox

conception. During the favourable opposition of 1877 he resurveyed the planet's surface, using the 8.5-inch equatorial of the Milan Observatory. He found on the continents a number of straight dark lines, which he called "Canali," or channels. In the next opposition of 1879 he confirmed this discovery, re-observed most of his old canali, and discovered many more. He considered these as permanent and natural features of the planet and likened them to the English Channel, or to the Channel of Mozambique. In fact his first map depicted them as narrow and sometimes winding channels separating the continents and dividing them into a great number of islands. In each succeeding map, however, these channels became narrower, straighter, and more numerous, until by 1888 the continents were furrowed by a fine network of intersecting lines, which had "all the distinctness of an engraving on steel."

For many years the reality of Schiaparelli's discovery was doubted, but in 1886 Perrotin noted a few of the larger canali and confirmed the existence of some of Schiaparelli's markings. Since that time many astronomers have observed the more prominent channels and to-day the reality of at least some of the markings first described by Schiaparelli cannot be doubted. But there are still a number of competent observers, provided with the largest instruments and in the clearest and best atmospheres, who are unable to see the net of fine sharp canali described in the later papers of the brilliant Italian. The beautiful draw-

ings of Keeler, Campbell, and Barnard may contain traces of the larger and longer channels, but they do not show the systems of radiating lines seen by Schiaparelli, Flammarion, and Lowell.

At the opposition of 1892 Pickering at Arequipa detected many of the canali and observed numerous small round spots, or lakes, at the intersections of the canali. But more notable was his discovery of streaks crossing and recrossing the darker portions of the planet; channels in the midst of the seas and oceans! Similar phenomena were seen by others, and mountain peaks and variations in level were discovered. The surface of the planet was found to be rough and uneven, and these irregularities of level were found on the darker as well as on the lighter, or land, portions of the planet. These observations robbed the seas and oceans of their water, and showed them to be but different coloured portions of the planet's disc.

The sequence in Martian discovery is thus tersely put by Lowell: "A surface thought at first to be part land, part water; the land next seen to be seamed with straits; and lastly the sea made out to be land." This story is paralleled in the case of the moon. The familiar dark markings of our satellite, "the man in the moon," were for many years thought to be seas and oceans and they still bear the old Latin names.

CHAPTER X

HAS MARS CANALS?

A CANAL is an artificial waterway for navigation or for irrigation. The word implies artificial construction by conscious, rational beings, working toward a definite, useful end. While a canal is usually a long, narrow, open ditch, the idea of size and shape implied in the word is subordinate to that of artificiality; the word is never applied to a natural waterway, however much it may resemble the ordinary canal. Channel, strait, river, and canyon are used for the various types of natural waterways. Before a canal can exist there must be conscious effort directed toward its construction, and there must be water to flow through it.

By the mere use of the word canal in connection with Mars, there is implied the existence of water on the surface of that planet and the presence of beings of sufficient intelligence and mechanical ability to construct elaborate works. There are certain faint markings on the surface of that planet which are loosely and unfortunately termed "canals," but are they canals in the literal sense of the word? Are the

assumptions implied in the use of the word justified, does there exist on Mars a single real canal? Schiaparelli, who discovered these peculiar markings, certainly did not think so, when he termed them "canali" and likened them to the English Channel. Popular and unscientific translations, however, turned the "canali" of 1877 into the canals of to-day and peopled Mars with a race of superior beings. Schiaparelli, himself, in his later days became convinced of the artificiality of these markings and the impossibility of their being the result of chance. Flammarion in France and Lowell in this country follow Schiaparelli and confidently assert that these markings are really canals and that Mars is inhabited; Lowell going so far as to say "What we see hints of the existence of beings who are in advance of, not behind us, in the journey of life."

There is nothing impossible, or even improbable, in the idea that life may exist on other worlds than our own. The earth is not unique, in the universe there must be many bodies of the same general characteristics. The earth is but one of a group of planets, which together with the sun form the solar system, and in the heavens there are countless millions of other suns, each perhaps, many certainly, attended by its swarm of planets. Life, even conscious intelligent life, flourishes under the most diverse conditions on this globe and it is hardly conceivable that among all the bodies of the universe our little planet is the only one capable of supporting some form of life. While

there are thus many reasons for believing that life may exist on other bodies of the universe, are there any sufficient grounds for supposing that life actually does exist on a particular body? The fact that many bodies may possibly sustain life, does not prove that Mars is inhabited. The question in regard to Mars is one of evidence, and the evidence rests upon the canali. Is there sufficient, is there any evidence that the canali are artificial, that they are true canals?

Lowell has spent many years in collecting evidence to prove this point, and puts forth this evidence in most enchanting style. Having at his command all the aids of modern science,—a 24-inch telescope of superb construction placed under the clear skies of Arizona,—he has gathered a great number of detailed drawings of the planet's surface, has measured and mapped the canali, and has succeeded in taking some remarkable photographs. A brief résumé of his work and theories will be of value in forming an opinion on the evidence he presents.

The canals as drawn by Lowell and his assistants differ radically from the "canali" first described by Schiaparelli and now recognised features of Mars' disc. The markings shown by the Flagstaff astronomers are geometric lines, looking as though they had been laid down by rule and compass. Each line is of uniform width from beginning to end and stretches across the planet's surface in an undeviated, unbroken course. Lowell likens their appearance to that of telegraph wires hung on poles and reaching from city

to city. In actual width these lines vary—2 to 3 miles is the estimated width of the narrowest, while from 15 to 20 miles is the probable value for the more distinct lines. The length of these lines is enormous; the longest exceeds 3500 miles, and many stretch 2000 and even 3000 miles across the surface of this strange planet. More remarkable than their length is the directness of these lines,—they always take the shortest, the great circle, course between the two points they join. Allowing for the larger size of the earth, such a line as the more distinct ones would stretch from London to Calcutta, crossing mountains, plains, and seas in an unbroken straight band forty miles wide.

These lines when plotted upon a chart form a complete network over the surface. At the extremities of each line others begin and extend to distant points of the planet. In but few cases do the lines cross one another, as a general rule they intersect at their ends. The surface thus appears to be cut up into a great number of meshes of various shapes and sizes. The mesh becomes smaller and the lines relatively more numerous near the poles. They appear to run into, or emanate from the polar caps. No part of the Martian surface is entirely free from this all-embracing network of lines; they furrow the bright continental areas and cross the dark "seas." The dark blue-green patches in the northern hemisphere are circumscribed and traversed by these lines; and all these lines and meshes are connected with and form a

continuation of the general system which covers the planet. The continuity and systematic arrangement of these lines is shown in the beautiful map reproduced from Lowell's *Mars and its Canals*.

This map shows another characteristic feature of the lines and meshes as drawn by Lowell,—the dark round dots at the principal intersections. They were first detected at Arequipa and appear both on the light and dark areas of the planet, and are termed by Lowell "Oases." In all 186 have been observed, of which number 121 lie in the light regions and 65 in the dark areas.

As if the phenomena already mentioned were not of themselves sufficiently peculiar, a still more weird observation is recorded. At times the lines, the so-called canals, appear double. They geminate and become two close parallel twin lines. This most strange sight was first witnessed by Schiaparelli in 1879. Since that date this assiduous Italian has observed the phenomenon many times and Lowell at Flagstaff has witnessed it several hundred times, and describes the gemination in the following words: "Where previously a single pencil-like line joined two well-known points upon the disc, twin lines, the one the replica of the other, stand forth in its stead. The two lines of the pair are but a short distance apart, are of the same size, of the same length, and absolutely equidistant throughout their course." When once seen as a double, the line remains thus for a period of four or five months. But not every line

Plate VI.

exhibits this peculiar appearance; many lines never appear double. In fact only about one eighth of the lines mapped at Flagstaff have ever been seen to geminate. And this property of appearing double seems to be inherent to certain definite lines; these lines and no others possess this property.

FIG. 25. DOUBLE CANALS OF MARS AS DRAWN AT THE LOWELL OBSERVATORY.

This gemination of the lines is seasonal; only in certain Martian seasons do the lines appear prominently double. The lines, themselves, seem to be

permanently double, to actually consist of two similar parallel lines, but the strength, the appearance, of the constituent lines varies. At times one line of the pair is relatively strong, the other weak, and the pair thus appears as a single line. In certain other seasons the constituents are equally strong, and the line appears clearly doubled. In the late Martian summer and fall of the northern hemisphere the doubles appear to their best advantage. Some three months after the summer solstice gemination occurs and for some four to five months the lines appear double, then one constituent fades away and the single stronger element alone is visible.

All these various appearances, or pseudo-appearances, are explained by Lowell as being due to an actual canal system, constructed for a definite purpose. Modern observations have conclusively shown Mars to be a dry planet, to have very little, if any, water on its surface. The so-called seas of fifty years ago are not real seas; islands and continents, shown on Proctor's map, are now known to be arid deserts. Upon these facts, Lowell builds his theory. According to him, what little water there is on the surface of the planet is confined to very restricted areas, appears as vapour in the atmosphere, and is deposited in winter at the poles in the form of snow. Under the action of the summer sun, this snow-cap melts and the water is conducted through the system of canals to various portions of the surface, irrigating and fertilising the nearby fields. Along the

canals and in the districts watered by them vegetation springs up, and the visible changes in the planet's surface are caused by the growth, maturity, and decay of this vegetation. What we see are not the canals, but the broad bands of vegetation on their banks; the seas are vast areas of irrigated land, resembling the reclaimed lands of our western deserts.

That these are canals and not natural waterways is suggested by their regularity, by their artificial appearance. No natural watercourses or earth cracks show any such regularity, and upon this regularity of appearance and systematic arrangement Lowell bases his opinions. Eight points he cites as evidence of their artificiality, and these eight points are[1]:

1. Their straightness.
2. Their individually uniform size.
3. Their extreme tenuity.
4. The dual character of some of them.
5. Their position in regard to the planet's fundamental features.
6. Their relation to the oases.
7. The character of these spots; and, finally,
8. The systematic networking by both canals and spots of the whole surface of the planet.

Upon the last point the greatest stress is laid; the canals are described as "a system whose end and aim is the tapping of the snow-cap for the water there semi-annually let loose; then to distribute it

[1] *Mars and its Canals*, p. 368.

over the planet's face." The canals inter-connect and seek well defined centres, their system covers the whole surface of the planet and allows a world-wide distribution of the tapped waters. Their arrangement shows the directing presence of an intelligence which seeks to utilise to its fullest extent the scanty supply of waters remaining upon the planet.

Such are Lowell's theories in regard to the canals of Mars and the observations upon which these theories and deductions rest. Are these observations correct? have they been confirmed by other competent observers? If confirmed (and the features of the disc be substantially as depicted by Lowell) are his conclusions logical and in accord with known physical laws?

In considering the question of the reality of the appearances, it must be remembered that the study of planetary details is attended with extreme difficulty. The visible disc is minute, and is seen through many miles of the shifting, trembling atmosphere. With the magnifying powers ordinarily used, Mars would appear somewhat the size of a silver quarter at the bottom of a stream three or four feet in depth. Currents and disturbances in the water render objects at the bottom hazy and indistinct; only at moments of perfect quiet can the lettering on the coin be seen. The faint markings on the planet's surface are at the very limit of our vision; on the borderland where perception ends and illusion begins.

Few observers have seen the lines as Schiaparelli

and Lowell depict them. The original "canali," the broad channels, have been repeatedly observed, but the thin pencil-like network of lines is more elusive. Young, with the 23-inch telescope of Princeton University, "failed to confirm" their existence. With low powers the planet appeared covered with faint markings in the same general positions as the "canals," but with higher powers these lines became mere shadings, undefined and irregular. The superb drawings of Keeler and Barnard made with the 36-inch Lick telescope are utterly unlike the clear-cut, ruler-and-compass effects of Lowell. Their drawings show soft, irregular shadings, and some broad, hazy, ill-defined streaks. Pickering, at Arequipa, observed numerous lines substantially like those in Schiaparelli's map, Campbell and Hussey at the Lick, Denning and Phillips abroad, have seen and mapped many lines and markings, but in none of their drawings do the lines stand out with the sharp, regular distinctness seen in the sketches from Flagstaff.

Maunder denies the physical existence of any lines: he considers the apparent lines on the planet's disc to be the result of optical illusion. The eye is often deceived, and when viewing very faint shadings and scattered dots there is often a tendency to perceive illusory lines. The dots are linked together and the faint irregularities are smoothed and straightened out into lines. Physical experiments and tests have been made, but with contradictory results. Maunder

tested a number of schoolboys by placing before them a scale drawing of Mars, showing all the principal features except the canali. In most of the copies made, the boys showed straight lines connecting the darker shadings and duplicating in many instances the disputed lines and canals of the planet. Flammarion tried similar experiments with negative results.

According to Newcomb the canaliform appearance "is not to be regarded as a pure illusion on the one hand, or an exact representation of objects on the other. It grows out of the spontaneous action of the eye in shaping slight and irregular combinations of light and shade, too minute to be separately made out, into regular forms."

A further strong argument against the reality of these canal-like forms is the fact that similar lines have been observed by Lowell on Mercury and on Venus. A comparison of the drawings [1] of the two planets as made at Flagstaff with the earlier drawings of Mars made by Schiaparelli and Lowell shows striking resemblances. In 1897 Lowell described the markings upon Venus in the following words: "They are not shadings more or less definite, but perfectly distinct markings. I have seen them when their contours had the look of a steel engraving." This reads exactly like the description of the canals

[1] See Chapter XIII. In a footnote in *Mars and its Canals*, published in 1907, Lowell writes: "The Venusian lines are hazy, ill-defined, and non-uniform."

of Mars. That one planet should have such curious markings is sufficiently strange; for three to have similar markings is incredible.

Douglass,[1] for many years a patient and painstaking observer of Mars and chief assistant at Flagstaff, now explains the fainter canal-like appearances as due to optical defects in the human eye. The larger markings and even some of the greater canals he considers as actual realities, but the excessive detail and the minute mesh-like arrangement shown by Lowell he considers psychological phenomena, illusions, and figments of defective vision. The double canals of Schiaparelli and of Perrotin are traced to similar causes, to what Douglass calls the halo illusion.

The reality of the gemination or doubling of the lines has also been questioned, yet Campbell, Hussey, and others have confirmed the observations of Schiaparelli and Lowell. Parallax, erroneous focusing of the eyepiece, optical illusion and defects have all been invoked to explain their peculiar appearance. It is well known that a minute error in the adjustment of the eyepiece will cause all the spider-lines in the reticle of a transit instrument to appear double. Single black lines drawn on a white disc will often appear doubled when viewed through a small telescope. If all the lines visible on a given date on Mars appeared double, and all appeared single on

[1] "Illusions of Vision and the Canals of Mars," *Popular Science Monthly*, May, 1907.

other nights, such an explanation of their origin might be possible. But this is not the case. Of two lines on Mars, similarly inclined, one will appear double and the other single. The same line under the same circumstances will always appear double, the other line always single. The consensus of opinion seems to prove the reality of the doubling.

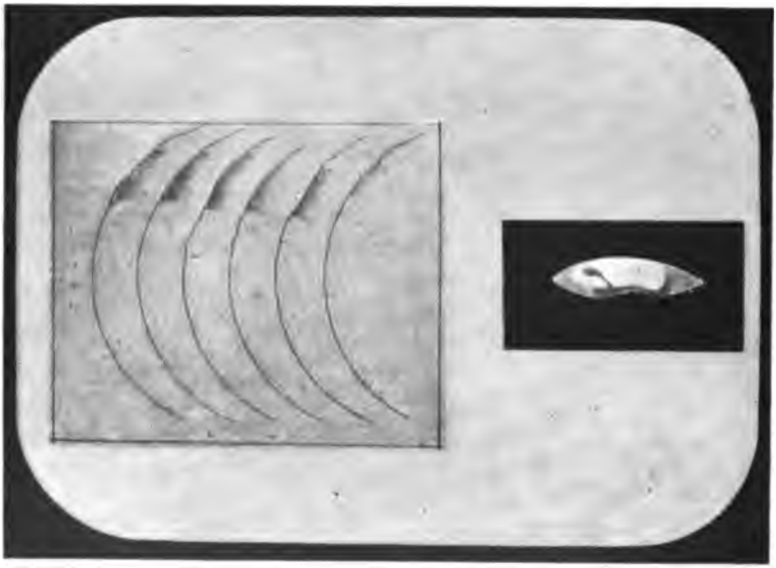


FIG. 26. IRREGULARITIES ON MARS.

The regularity, the straight, undeviating course of the lines upon which Lowell so strongly insists, is far from being proof of their artificiality. It is proof rather of illusion, of some optical effect, or of natural causes. Mars is not a perfectly smooth globe, its surface is undulating; there are hills, valleys, and

mountains even. Numerous observations of irregularities have been made at the terminator, or boundary between that portion of the planet upon which the sun shines and that upon which it is night. Just as on the moon, so on Mars, differences in elevation can be best determined along that line of the surface at which the sun is just rising or setting. But on account of the rapid rotations of the planet and its great distance these observations are extremely difficult. Lowell calculates that differences of level of less than 2500 feet cannot be distinguished. Now small bright projections like mountain peaks have been seen, so also have flattenings and slight hollowings.[1] Some of the larger projections noticed were undoubtedly due to clouds, but the flattenings and general irregularities must be due to the uneven surface of the planet itself. Hills, plateaus, and mountains of four or five thousand feet altitude are indicated by the observations, and higher ranges are by no means unlikely. Artificial features, the work of intelligent beings, would follow and be conditioned by the natural contour of the surface. The shortest distance between two points is often the most difficult and the longest way round is frequently the quickest way home. The lines or so-called canals indicated by Lowell always take the direct, the shortest possible path in connecting any two points, regardless of any natural features, regardless of probable hills and valleys. "The lines run straight throughout their

[1] Report of Council R. A. S., Feb. 8, 1895, *Monthly Notices*, vol. lv., No. 4.

course." Does this indicate the presence or the absence of a directing, constructive intelligence?

The geometric appearance of the entire system of lines is not a proof of artificiality. Geometry is but a translation of natural forms into the precise language of mathematics. Snowflakes, rock crystals, and many other substances assume beautiful geometric forms and shapes. Geometrical shapes are everywhere present in nature, but nowhere on the vast scale

Fig. 27. Drawings of Mars made by E. E. Barnard.

shown by the Lowell lines and markings. Because they show geometrical forms on a vastly larger scale than any natural phenomenon on the earth, Lowell reasons that they cannot be the result of natural forces. Mere size thus becomes the chief argument of those who favour the artificiality of these strange markings.

Again the shape of the planet is very nearly that which would be assumed by a rotating fluid mass of the same general size and density. The polar com-

pression is about $\frac{1}{220}$, although early observers made it considerably more than this. Like the earth, its surface is probably very nearly in fluid equilibrium and the flow of water should be governed by local variations in the height of the surface, by the trend of hills and valleys. But according to those who see in the markings a vast irrigating system, the water flows from the north during the northern summer. Starting at the polar cap, it sweeps through the network of canals through the temperate regions, past the equator, and fertilises the plains to some 35° south latitude. During the next season the flow is reversed,—the south polar cap melts and the water flows northward, finally reaching 35° north latitude. Thus over that great part of the surface lying between 35° south and 35° north latitude (from Buenos Ayres in the south to Washington in the north) the water in the so-called canals flows in opposite directions in winter and in summer; flows up-hill as readily as down-hill! To overcome the obvious physical impossibilities of such a system, Lowell is forced to the conclusion: "No natural force propels it [water], and the inference is forthright and inevitable that it is artificially helped to its end." The engineering feat here proclaimed staggers the imagination.

To push speculation and imagination to this extreme is farcical when the simplest and most elementary of the planetary conditions are still unknown. There is no direct evidence that water even exists upon the surface of Mars: its presence is inferred from

the behaviour of the polar caps. Whether this inference be correct or not, is an open question. The atmosphere of Mars is extremely thin, and remarkably free from clouds and masses of vapour. The force of gravitation at the surface of the planet is only 0.38 that of the earth. Hence, if each square yard of Martian surface were supplied with the same amount of atmosphere that is over each square yard of the earth's surface, the atmospheric pressure would be only 0.38 that we are accustomed to. Instead of at thirty inches, the barometer would stand at less than twelve inches; the atmosphere would be as thin and rarified as at the tops of the highest mountains on the earth. It would seem, therefore, as though the temperature on Mars should be exceedingly low, far below the freezing point of water. This probability of a low average temperature is heightened by the fact of the planet's distance from the sun. Mars is a little more than one and a half times as far from the sun as the earth, and receives only about forty-three per cent. as much heat as does the world. Such a diminution in the amount of heat received by the earth would cause an age of perpetual snow and ice.

In the chapter on the Heat and Light of the Sun the temperatures of "black" bodies at various distances from the sun were noted. At the average distance of Mars such a body would have a temperature of —22° Fahrenheit; that is, if Mars be a body whose temperature depends solely upon the heat received from the sun, if it absorb and radiate heat

freely, then the temperature of Mars must be some 54° below the freezing point of water. The average temperature of the earth's surface is not far from its theoretical temperature, as calculated for a body at its distance from the sun, and there seems to be no valid reason why the temperature of Mars should vary greatly from the theoretical value.

Unless, therefore, Mars has a considerable store of native heat, or unless its atmosphere differs considerably from our own, the surface temperature must be far below that of the earth. There is no evidence of internal heat. Mars is smaller than the earth, and is probably as old or older, and, therefore, its internal heat is probably much less. On the other hand, if the Martian atmosphere is far richer in water vapour than our own, it might prove to be a more efficient blanket, letting in the short intense heat and light rays of the sun, but hindering the escape of the long dark rays radiated from the soil of the planet. Thus an atmosphere full of water vapour might act as a mechanical trap for catching and storing up the solar heat. To such an atmosphere Lowell attributes the mild climate which he assumes prevails upon Mars, a climate having "a mean temperature colder than that of the earth, but above the freezing point of water." In other words, on the one hand, he explains the presence of and the artificiality of the canals by the scarcity of water upon the planet, by the necessity of husbanding every drop of the precious fluid; on the other hand he accounts for the temperature

necessary for the existence of free water by assuming an atmosphere laden with water vapour. He conjures up a dry, parched desert in which sand storms abound, covered over with a moist, saturated atmospheric blanket!

If no such atmospheric blanket exist, then the temperature of Mars must be many degrees below zero, and the daily variation between day and night must be great. In this regard the conditions should approach somewhat those existing on the moon. During the day the surface would be heated to a considerable degree by the direct rays of the sun, but at night the surface would radiate forth its heat and the temperature fall to 100° or 200° below zero. In this regard it should be noted that only that portion of the surface directly lighted by the sun is visible; that portion of the planet upon which it is midnight is always turned away from the earth.

Certain theoretical considerations of the kinetic theory of gases have been adduced to show that water vapour cannot exist in the Martian atmosphere. The molecules of a gas or vapour are always in rapid motion, and for a given temperature and pressure the molecules of each gas have a certain definite average velocity; the molecules of the heavier gas moving more slowly than those of the lighter. Hydrogen molecules, for example, under atmospheric pressure and at a temperature of 32° Fahrenheit, move, on the average, with a velocity of more than a mile per second. This is the average velocity; many molecules

move faster than this and many move more slowly, some are moving very slowly indeed and some are moving with enormous velocities. In a gas at ordinary pressures and densities the free path of a molecule is extremely short; is measured in the millionths of an inch. In fact a molecule is no sooner started on a course, than it collides with a neighbour and the direction of its motion is changed. The denser the gas the shorter is the free path; only in gases of extreme rarity are the paths of a sensible length.

The average velocity of a molecule of some of the more common gases is given in the little table below:

Hydrogen	1.14	miles	per	second
Water vapour	0.38	"	"	"
Atmospheric air	0.30	"	"	"
Oxygen	0.29	"	"	"
Carbon dioxide	0.24	"	"	"

These are the velocities at atmospheric pressure and at the freezing point of water. As the temperature of the gas increases, so also increases the velocity of its molecules; the average, or mean velocity, being proportional to the absolute temperature.

Now, the height to which a ball will rise in the air depends upon the velocity with which it is thrown. If it could be started upward with sufficient speed, it would overcome the attraction of gravitation and pass away into space. There is, thus, a certain definite speed which the earth can control; faster than which, if a body be started, it will permanently escape from the earth's control. This definite speed of con-

trol depends upon the mass and size of the attracting body, and thus varies for the different bodies of the solar system. The velocities of escape, as they might well be called, for several of the different bodies are tabulated below.

For the Moon	1.48	miles	per	second
For Mercury	2.45	"	"	"
For Mars	3.13	"	"	"
For Venus	6.37	"	"	"
For the Earth	6.95	"	"	"
For Jupiter	37.16	"	"	"
For the Sun	380.00	"	"	"

If now a molecule in the outer layer of the earth's atmosphere be moving with a velocity of seven miles per second it will permanently escape from the earth. The molecules of no gas have an average speed so high as this, but in all gases some few molecules are always moving with enormous velocities. In light gases the number of molecules moving with high speeds are greater than in the heavy gases, and the rate at which the different gases escape will vary accordingly. Hydrogen escapes much more freely than water vapour, and water vapour would go long before atmospheric air.

The moon has lost her atmosphere, although she is able to control velocities several times that of the average molecule of atmospheric air. The earth's atmosphere contains no free hydrogen, yet the earth can control a speed six times that of the average hydro-

gen molecule. The molecules of water vapour, so abundant in our atmosphere, are much more sluggish than those of hydrogen—the velocity of the average water vapour molecule is but one eighteenth the velocity of escape. It would seem, therefore, as if sufficient time had elapsed for the bodies of the solar system to lose from their atmospheres those gases whose molecules move on the average with velocities one sixth as great as that which the planet can control.

The velocity of escape from Mars is but 3.13 miles per second, only eight times the velocity of water vapour molecules. Thus water vapour would escape from Mars very nearly as readily as hydrogen does from the earth. Mars is as old as the earth, and the water vapour in its atmosphere must be nearly, if not quite, exhausted by now. On the other hand the molecules of carbon-dioxide move with an average velocity only about one fourteenth that which Mars can control. This heavy and sluggish gas would, therefore, escape with difficulty and is probably yet abundant upon our interesting neighbour.

While, thus, the kinetic theory does not prove the impossibility of water vapour existing upon Mars, yet it goes far toward showing such existence to be extremely improbable. But if there be no water vapour on the planet, then the generally accepted explanation of the polar caps must be revised.

From all the conflicting data one conclusion may safely be drawn and this is, that very little is actually known in regard to the conditions existing on Mars.

There are, to be sure, a great mass of observations and many beautiful drawings, but no thoroughly satisfactory interpretation of the phenomena and of the drawings has yet been adduced. Many of the problems, especially those of the canals, presented by this interesting planet are psychological, not physical.

All that can be definitely stated in regard to the surface conditions on Mars may be briefly summed up as follows:

1. The surface of the planet shows the presence of matter in two distinct forms, formerly thought to be land and water and now called by some desert sands and irrigated plains. But in what way the lighter coloured portions of the surface differ from the dark markings is not definitely known. The moon, which has neither air nor water, has light and dark patches.

2. The planet is surrounded by a very light atmosphere containing vapours analogous to those of water or carbon-dioxide. This atmosphere cannot be one fourth as extensive as our own and is probably even far below this limit.

3. The atmospheric vapours are condensed by cold and, during the winter months, are deposited at the poles in the form of the "ice-caps." These disappear during the Martian summer. Seasonal changes are also shown by the dark markings scattered over the surface.

4. The average temperature of the planet is much lower than that of the earth, and is probably

below the freezing point of water. The theoretical temperature of the planet is —22° Fahrenheit.

5. The surface of the planet is rough, uneven, and shows a mass of faint detail, which appears differently to different observers. The objective reality of the straight-line markings, or so-called canals, has not been satisfactorily established.

CHAPTER XI

THE OUTER PLANETS

JUPITER. Next to the sun and moon, Jupiter is the most conspicuous object in the heavens. Venus is more brilliant, but is seen only in the morning and evening twilight, while Jupiter is often overhead at midnight, and outshines by far the brightest fixed stars. This prominence is not fictitious, is not caused like that of the moon by the nearness of the planet. Jupiter is the largest planet of the solar system, larger and more massive than all the other planets put together. Jupiter is, in fact, a miniature sun, the centre and controlling body of a small planetary system of its own—two of its satellites are larger than the planet Mercury, and the largest is but a trifle smaller than Mars.

The orbit of this giant planet is of but little interest, except to the mathematical astronomer. The mean distance of the planet from the sun is five and a fifth ($5\frac{1}{5}$) times that of the earth, or a little over 483 million miles. The orbit is considerably more eccentric than those of Venus and the earth, its departure from circular form being sufficiently great to be appreciable in an ordinary diagram. The ec-

centricity is a little less than $\frac{1}{20}$, and the sun is, therefore, displaced some 22 million miles from the centre. This causes a corresponding variation in the distance between the planet and the earth at times of opposition, the closest approach of the two bodies occurring when Jupiter is near its perihelion, a point which the earth passes in October of each year. At an October opposition, therefore, Jupiter will be most favourably situated for observation and may approach the earth as close as 369 million miles.

Around this huge ellipse Jupiter travels at an average speed of some eight miles per second, taking 11.86 years to complete one circuit. Its synodic period, or time from opposition to opposition, is 399 days or within a few days of one year and one month. Thus the last opposition occurred in the latter part of December, 1906, and the next will fall on the last of January and the first of February, 1908; there being no opposition in 1907. After 1908 the oppositions will occur about a month later each year, that of 1909 happening in March. The earth passes the aphelion of Jupiter's orbit in April, and so for the several years that the oppositions occur in the spring, Jupiter will be in its most favourable position for observation.

With even a small telescope Jupiter is a beautiful object; the disc is distinctly oval and is crossed by broad shadowy bands. These belts are parallel to the longer axis of the disc and are of a cloud-like form, changing in shape and detail from night to

night. Bright spots appear and disappear and the surface is one of continual change. In a single evening spots and markings in the belts may be seen to pass across the face of the disc, indicating a rotation of the planet in a little less than ten hours, the shortest known period of rotation in the solar system.

To this rapid rotation is due the marked oval form of the disc; the surface of the planet being in equilibrium between the central attraction of gravitation and the centrifugal forces of rotation. In form Jupiter is an oblate spheroid, the polar or shorter axis lying at right angles to the plane of the belts. The oblateness is $\frac{1}{17}$, or the polar diameter is one seventeenth part less than the equatorial. In miles the equatorial diameter is some 88,200; the polar some 83,000. Thus the equatorial diameter of Jupiter is over eleven times that of the earth; the mean diameter of the planet, on account of the great oblateness, however, is a trifle less than eleven (10.92) times the mean diameter of our world. In bulk Jupiter is more than thirteen hundred times as large as our little planet.

The mass of, or amount of matter in, this huge globe can be most accurately determined from the motions of its satellites. Under the law of universal gravitation the periodic time of a planet or satellite about its primary depends solely upon its distance from and the mass of the central body about which it revolves. The greater the mass of the central body, the faster its planets will revolve in their orbits; if

the sun's mass were suddenly increased fourfold the year would be halved. Now the first satellite (Io) of Jupiter is but a trifle farther from that planet (261,000 miles) than the moon is from the earth (239,000 miles) and, therefore, if Jupiter and the earth were of the same mass, Io would complete one revolution in its orbit in a little more than one lunar month, or in about 31 days. The actual periodic time of Io is only 42 hours, or between one seventeenth and one eighteenth ($\frac{1}{17.8}$) that of the earth's satellite. To cause a body to revolve at this rate the mass of the earth would have to be increased as the square of 17.8 or very nearly 316 fold, and hence the mass of Jupiter must exceed that of the earth in this proportion. According to Newcomb's most careful determination the combined mass of Jupiter and its satellites is $\frac{1}{1047.355}$ that of the sun, or 314.5 times that of the combined mass of the earth and moon.

This mass is much less than would be expected from the size of the planet and shows that its density is small as compared to the terrestrial planets. In fact the average density of Jupiter is a little less than one quarter that of the earth, but little more than that of water. In this regard the planet very closely resembles the sun and seems to be a globe of gaseous matter. The interior must be under enormous compression, and may possibly be solid, but the outer portions, at least, are composed of gases and vapours.

This gaseous character of the surface portions is clearly indicated by the peculiarity of the planet's

rotation; the equatorial regions rotate in a shorter time than do those in higher latitude. Cassini noted this and pointed out the similarity to the rotation of the sun. As a general rule equatorial markings rotate in periods averaging about nine hours and fifty minutes, while spots midway between the equator and poles average some five to six minutes longer. But different spots in the same latitude often give different results; bright white spots appear to rotate faster than do the darker markings. In 1890 a small spot was observed to overtake and pass the "Great Red Spot," skirting around its southern edge. The rotation periods of these two adjacent markings differed by more than five minutes, or about $\frac{1}{120}$ part of the whole period. In other words in a single rotation of the planet, in less than ten hours, the smaller spot gained nearly 2500 miles on the larger; the spots passed each other at a speed of nearly 250 miles an hour. In our atmosphere fifty miles an hour is a gale and one hundred miles an hour a hurricane which levels and destroys all before it. Yet the "Great Red Spot" of Jupiter maintained itself for years against a current of matter, sweeping by with a velocity twice and three times that of a hurricane.

This red spot was the most permanent and the most remarkable of Jupiter's markings. It was first seen and recorded by Pritchett in July, 1878; although several years before that date an "elliptical ring" had been seen in the latitude in which the spot afterwards appeared. By the latter part of

1878, the spot seemed like a rosy cloud attached to the southern equatorial band. For several years it was the most conspicuous marking on the planet; it was over 30,000 miles long and some 7000 wide,

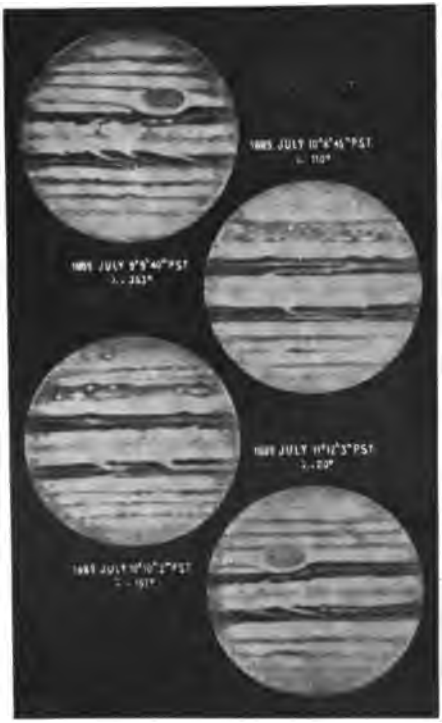


Fig. 28. Jupiter in 1889.

while its colour deepened until it became a dull brick-red. It was not, however, a permanent, fixed part of a solid planet for it drifted over the surface. Its period of rotation changed; by 1883 it was revolv-

ing several seconds more slowly than when discovered. Again a few years later its period was once more lengthened. These changes were unmistakable, the time of rotation in each case having been determined within half a second. If the faster speed represented the true rotation of that portion of the planet's disc, then, at the slower speed, the spot must have steadily drifted to the westward and must have made a complete circuit around the planet after the lapse of a few years.

These changes in the speed of rotation of the spot were accompanied by radical changes in its appearance. Early in 1883 it had become semi-extinct and had faded so as to be barely visible. In 1886 it regained some of its old time strength and colour, and at the same time it was apparently retarded, its period being appreciably lengthened. Three years later it had again faded to a pale pink colour and although it afterwards revived slightly for a time, yet it is now always inconspicuous and even invisible. Yet the position the spot occupied can still be made out—it seems to have left a hole, or a bay, in the edge of the great southern belt.

Many attempts to explain the nature of this spot have failed; no terrestrial analogy will suffice. It was not a fixed portion of the planet, it was not self-luminous, and it was not a mere cloud floating in the atmosphere. Some observations seemed to indicate that it was fed from below, that it was somewhat analogous to the spots and faculæ of the sun.

Jupiter is in reality a semi-sun—a sun which has just ceased to shine. In fact portions of Jupiter may even be sufficiently hot to be self-luminous. The albedo, or reflecting power, of the surface is extremely high: according to the measurements of Müller in 1893 the planet, as a whole, reflects seventy-five (75) per cent. of the sunlight which falls upon it. Venus reflects but fifty (50) per cent. and white paper less than seventy (70). Thus the total amount of light which we receive from Jupiter may be reflected sunlight, but the disc of the planet is far from uniform. The general surface appears, not white, but of a deep yellowish tinge, and the bands are of a darker brown or chocolate colour. It would seem as though such a surface could not reflect a greater proportion of incident light than pure white paper, and as a natural inference it has been suggested that some of the light is native to Jupiter. Certain bright, white spots occasionally appear on the disc, and these shine with far greater brilliancy than do any other portions of the planet; the albedo of these spots must be very high, nearly, if not quite, one hundred. These spots may even give out more light than falls upon them.

But, as against this view, the spectroscope does not give any indication of native luminosity. The spectrum of Jupiter is practically identical with that of the sun; it shows however some traces of atmospheric absorption. The spectroscope apparently shows the planet to be surrounded by a dense, cool atmosphere,

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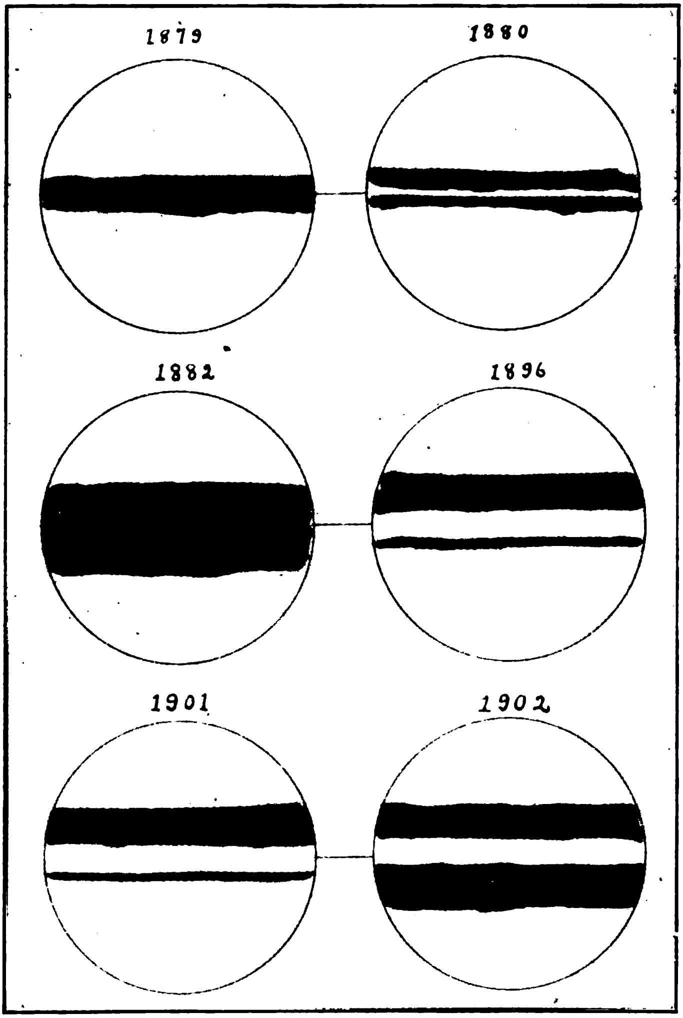

FIG. 29. CHANGES IN JUPITER'S BELTS AS DRAWN BY HOUGH

into which the sunlight penetrates but a short distance. Again the phenomena of the satellites, in transits and in eclipses, show that the luminosity of the planet must be extremely feeble, if, indeed, it emits any light. When a satellite passes into the shadow of the planet, it disappears from view; when a satellite passes between Jupiter and the sun, its shadow, cast upon the disc, appears of an inky blackness. Some curious "black transits" of the satellites have been witnessed: the satellite appearing as a black spot against the bright disc of the planet; so black indeed as to be mistaken for its own shadow. These black transits can be explained by the relatively low local albedo of the satellite, which, therefore, reflects but little light, and appears dark by contrast.

In the light of our present knowledge Jupiter appears a body midway in development between the sun and the earth. The planet probably has a small solid nucleus surrounded by immense masses of dense vapours. The temperature of the whole planet is exceedingly high, that of the nucleus may even approximate toward the effective temperature of the sun's surface. This temperature gradually diminishes until at the surface it is hardly sufficient to make the planet self-luminous, but the energy of the internal heat gives rise to violent motions and the layers of gaseous matter are in rapid circulation.

One of the most important discoveries in physics was made by the Danish astronomer, Roemer, 1675,

from observation of Jupiter's satellites. The eclipses of each satellite evidently should follow one another at regular intervals, depending as they do, upon the motion of the satellite in its orbit, which can readily be determined. The eclipses occur uniformly later than their predicted times as the earth recedes from Jupiter and earlier when the earth is approaching that planet. This retardation of the eclipses as the earth recedes, is precisely the same for the four satellites and is caused by the light having to travel a trifle farther each time to overtake the retreating earth. When the earth has reached its maximum distance from Jupiter all the eclipses occur some sixteen minutes late. But at this time the earth is just the diameter of its orbit farther from Jupiter than when nearest that planet, at opposition. The whole retardation (sixteen minutes, forty seconds) is thus the time required for light to travel over a distance equal to the diameter of the earth's orbit. When this distance is known then the velocity of light in miles per second can be found.

Roemer thus found an approximate value for the "equation of light," the time required for light to travel the distance between the earth and the sun, and for the velocity of light throughout space. At the present day the velocity of light can be determined more accurately by experiments in a physical laboratory, because the times of disappearance of the satellites cannot be observed with precision. As a result of such experiments by Michelson and Newcomb, it is

now known that light travels in vacuo at the speed of 299,860 kilometres per second, with a probable error of less than 30 kilometres. This corresponds closely to 186,330 miles per second; at which speed it takes the light of the sun 498.5 seconds (8 minutes 18.5 seconds) to reach the earth.

Saturn. Saturn is a world in the making; a planet in the earlier stages of development. Far lighter than Jupiter, less dense even than water, this globe must be a vast mass of rolling, seething vapours. At the centre there is probably an intensely hot solid, or semi-solid, nucleus, but the greater portion of the huge ball, some 71,000 miles in diameter, is composed of cooling and condensing vapours, gases kept in rapid circulation by the intense heat of the central core.

This is the characteristic modern discovery in regard to these great planets. Less than half a century ago these bodies were thought of as similar to the earth, cool, dark, habitable worlds. Proctor in 1865, in *Saturn and its System,* wrote: "When we consider the analogy of our own planet, it seems impossible to doubt that Saturn is inhabited by living creatures of some sort. . . . Whether it is inhabited, as yet, by comparatively rudimentary races, or whether it is already peopled by reasoning and responsible beings, capable of appreciating the wonders that surround them, and adoring their Creator—it is not given to us to know." To-day we know that Saturn cannot be the abode of any form of life; its temperature is

so high that metals and rocks melt, and the surface that we see is but the outer portions of constantly shifting masses of clouds and vapours.

Saturn has been known from prehistoric times. While by no means so bright as Jupiter or Venus, yet it is a conspicuous object in the midnight sky, shining with a dull red-yellow light, and being surpassed in brilliance by but three or four of the heavenly bodies. Owing to the immense size of its orbit, nine and a half times that of the earth, its motion among the stars is extremely slow. On the whole Saturn moves forward about twelve degrees a year and completes a circuit of the heavens in a little less than twenty-nine and a half (29.46) years. But once each year, when in opposition, the planet retrogrades through an arc of some five (5°) degrees. At this time its motion is sufficiently rapid to be noticeable to the unaided eye, especially if the planet happens to be near a bright star. In between five and six days Saturn passes over an arc equal to the apparent diameter of the moon's disc.

The synodic period of Saturn, the interval from opposition to opposition, is 378 days or one year and twelve to thirteen days. Thus each succeeding opposition occurs about two weeks later each year. In 1907 Saturn was on the meridian at midnight of September 16th, when it appeared some $4\frac{1}{2}°$ south of the celestial equator. For several weeks before and after this date the planet was conspicuous and was in a favourable position for observations.

In 1908 the opposition will occur on September 28th, and in 1909 and 1910, during the month of October.

When viewed through a modern telescope Saturn presents a most magnificent and unique appearance. The great globe is distinctly oval, is crossed by dark, heavy bands, and, unlike any other body, it is surrounded by a system of broad, flat rings. These rings were long a puzzle to astronomers. Galileo first saw them in July, 1610, but he utterly failed, then or afterwards, to recognise their true character. His telescope magnified but thirty-two times and the definition was poor and the field small. To him Saturn appeared accompanied by two minor discs, one on either side of the planet, which overlapped the main or central disc and gave the planet a peculiar triform shape. To Kepler he wrote, "Saturn consists of three stars in contact with one another." A year and a half later these appendages of the planet disappeared and Saturn showed a clear round, though slightly oval, disc. Again a few years and the appendages reappeared, being at first small, but gradually growing larger and larger and changing their shape, until to Galileo they appeared like great handles.

During the next forty years many curious drawings of Saturn and his children were made, and many and varied were the explanations of the startling phenomenon of their appearance and disappearance. Huyghens, the Dutch astronomer, enlarged and im-

proved the telescopes of his time, finally making one 123 feet in focal length. With this he examined Saturn and after several years' patient study he announced in 1659 that the planet was encircled by a thin ring, inclined to the ecliptic. By this inclination he explained the varied appearance of the ring, and showed that its disappearance was caused by its edge being temporarily turned towards the earth.

This ring is extremely thin, but quite broad, the diameter of its outer edge being over twice that of the planet itself. The ring is parallel to the equator of the planet and inclined about 28° to the plane of the earth's orbit. As Saturn revolves about the sun the plane of the ring always remains parallel to itself. This plane cuts the plane of the ecliptic in a line stretching between longitudes 166° and 346° When, therefore, Saturn reaches either one of these two points, the plane of the ring will pass through the sun, and the ring will be seen edgewise by an observer at the sun. The earth is comparatively so near the sun that the ring will also appear edgewise to us, and it is so thin that it appears as a mere line, and is invisible except with powerful telescopes. Twice in each revolution of Saturn the ring thus disappears, and these disappearances occur at intervals of approximately fifteen years. In 1907 the ring was thus invisible, in April it appeared as a line less than six hundredths (0″.06) of a second wide.

After 1907 the ring will appear to widen out, and the sun will shine on its southern face, which for the

next fifteen years will be visible. After a lapse of some seven and a half years, or in 1915, Saturn will reach that point in its orbit where the ring appears at its maximum width. As the plane of the ring is inclined at an angle of 28°, the ring, at this point, will appear as an ellipse, the minor axis of which is a trifle less than half the length of the major. After passing this point of maximum visibility, the ring will grow narrower and narrower, until in 1921 it will again disappear. Shortly afterward the northern side of the ring will become visible, gradually widen out, and remain in sight for fifteen years.

FIG. 30. SATURN AND ITS RINGS.

A few years after Huyghens's discovery of the true nature of Saturn's appendage, Cassini in Paris found a thin black stripe running completely around the ring, and announced that the ring was really composed of two concentric rings, the inner one being the broader and brighter of the two. This dark space separating the two rings is now known as *Cassini's*

division. Many other similar divisions have from time to time been suspected; but only one of these, however, has been recognised as permanent. This is the so-called *Encke division,* which separates the outer ring into two nearly equal parts. In 1850 Bond of Harvard discovered what for a long time was taken for a third ring, being inside the other two. This, the *crape ring,* is faint as compared to the other two; it appears dusky and very indistinct near its inner edge. There is apparently no distinct separation between the inner edge of the bright ring and the outer edge of the crape ring, although some observers, notably Dawes, have at times noted a distinct black band between the two. The crape ring is rather a grey border to its more brilliant neighbour.

This system of rings is beautifully shown in the drawing of the planet. The Cassini division is sharp and distinct, the Encke faint and rather hazy. The dimensions of Saturn and its rings, according to the latest measures by Barnard, are given in the table below:

Equatorial diameter of planet............	76,470	miles
Diameter of inner edge "crape border"...	88,200	"
Diameter of outer edge of inner ring......	146,000	"
Diameter of outer edge of outer ring......	172,600	"
Distance between planet and crape border..	5,865	"
Width of crape border	10,900	"
Width of inner ring......................	18,000	"
Width of Cassini's division...............	2,240	"
Width of outer ring......................	11,060	"

These rings are not perfectly uniform, nor are they constant. The shadow cast by the planet upon the ring system often shows irregularity, as if it fell upon an uneven surface. When seen nearly edge on, the rings present an uneven line, showing that they are not quite plane, or that they vary in thickness. The many divisions seen by such observers as the Struves, Dawes, and others indicate that the rings change their shape and character to a certain limited extent.

Until comparatively recent times the rings were thought of as solid, continuous bodies; each ring a broad flat band of solid matter. Laplace was the first to investigate the structure of the ring system from a mathematical and physical standpoint. He showed that a simple broad ring could not exist long, the attractions of the planet would tear it to pieces; but that a narrow irregular ring might be stable provided it rotated about the planet. Laplace conceived of the rings as consisting of a great number of narrow rotating rings, each being non-uniform and varying in thickness and density. In 1851 Pierce investigated the subject along the same lines and demonstrated the impossibility of the rings being solid, and in 1857 Clerk Maxwell, in the Adams Prize Essay, proved that they could be neither solid nor liquid. He demonstrated conclusively that the rings are mere swarms of minute separate particles, each travelling about the planet in its own independent orbit. The continuity of the rings is one of appearance only, not of substance.

While this conclusion of Maxwell's was based upon pure mathematical reasoning, it was generally accepted as the only possible explanation of the ring system. In 1895 Keeler brought out direct, observational proof that this theory is correct. By means of the spectroscope he was enabled to measure the speed of rotation of various parts of the ring, and found that the inner edge revolved with great rapidity. This speed gradually diminished until the outer edge was reached, and every part of the ring system moved with the speed a satellite should have were it situated at the same distance from the planet. The observations upon which this beautiful result depends were most delicate, and will always be regarded as among the classic observations in astronomy.

The disc of Saturn is a faint reflection of that of Jupiter; it is crossed by bright and dark belts and presents otherwise few distinct, or permanent, markings. The edges of the disc are darker than the central portion and the bands fade out and become indefinite as they approach the edge. The bands often show faint rose-coloured tints and indistinct markings and at times brilliant white spots appear and remain visible for several weeks. From such a spot on the equatorial belt Hall determined in 1876 the period of rotation of the planet. He found that the length of Saturn's day is but little greater than that of Jupiter's, that the planet rotated upon its axis in 10 hours and 14 minutes. This agreed very closely with a previous determination by Herschel, who found for

this period 10 hours and 16 minutes. But in 1903 Barnard discovered some bright spots in northern latitude 36°, and from the observations made upon them by many observers Denning deduced a period of 10 hours 38 minutes 3 seconds. Thus, as on Jupiter, different portions of Saturn rotate at different speeds, the equatorial portions rotating at the greater velocity. There must, therefore, exist a great equatorial current which has the enormous velocity of 800 or 900 miles an hour relative to other portions of the surface. Late in the year 1903 there was a marked acceleration in rate of rotation; observations on fifteen bright and dark spots gave a mean period of 10 hours 37 minutes 56 seconds, some seven seconds less than found earlier in the year. All this indicates extreme mobility in the materials composing the visible surface of the planet, a mobility inconsistent with any solid or fluid matter.

The gaseous condition of the greater portion of Saturn might easily be inferred from the average density of the planet. The mean diameter of Saturn is nearly nine times that of the earth and its volume 740 times that of our little globe. Yet the mass of this great globe is, according to Bessel, only ninety-five times that of the earth, and its average density, therefore, less than one eighth that of our planet, but seven-tenths that of water. In other words Saturn is so light that it would float on water, its density is about that of cork. The conception of Saturn, which seems most probable to-day is that the planet con-

sists of a small, but massive solid nucleus, surrounded by an immense gaseous atmosphere filled with minute liquid particles; the whole at an extremely high temperature.

Uranus and Neptune. These planets are interesting on account of the history and circumstances attending their discovery. They are so distant that practically nothing is definitely known as to their physical constitution; their telescopic discs are so small that no certain and definite markings can be made out. The mean distance of Uranus from the sun is nineteen (19) and that of Neptune thirty (30) times that of the earth, while the apparent diameter of the former is four (4″) seconds, and that of the latter but two and a half (2″.6) seconds of arc.

In a general way these two bodies resemble Jupiter and Saturn; they are both huge globes of small average density. Uranus is about 32,000 miles in diameter, while Neptune is slightly larger, its diameter being some 35,500 miles; in density the two bodies are midway between Jupiter and Saturn, their average densities being a little greater than that of water. The spectra of these bodies, however, differ radically from those of all the other planets. Instead of showing the usual Fraunhofer lines of reflected sunlight, their spectra show six broad absorption bands, some of which correspond to the hydrogen rays, and one to the "red-star" line of Jupiter and Saturn. These absorption bands indicate that the light received from these planets has passed through a very dense med-

ium, containing substances quite unknown in our atmosphere. Some observations seem to point toward the presence of light originating upon these planets, but definite proof of this is yet lacking. As opposed to this view, however, are certain spectrographs obtained by Huggins, who found the spectrum of Uranus to be purely solar in character, showing the Fraunhofer lines without a trace of absorption.

Uranus was discovered by Wm. Herschel on March 13, 1781, when he first noted an object with a planetary disc. After watching this object for two or three nights he detected its movement among the stars and announced the discovery of a comet. Lexell computed the orbit of this new body, found that its path about the sun was nearly circular, and after a few months he became convinced that it was a planet. Within a year from its discovery, Uranus was universally recognised as a new member of the solar system. Herschel, until then a comparatively unknown amateur, became at once one of the most prominent astronomers of the world; he was knighted and pensioned by the King and furnished with funds for building his famous four-foot reflecting telescope. He called the new planet "Georgium Sidus," in honour of his patron, King George III.; others called it "Herschel," while the Germans named it "Uranus." This last name, first suggested by Bode, finally prevailed and since 1850 no other has been used.

In this discovery Herschel was more fortunate than

some of his predecessors, who had observed the planet many times but had failed to recognise its character. Flamsteed had observed it as early as 1690 and Lemonnier, at Paris, observed it no less than twelve times, during 1768 and 1769. Had the latter reduced his observations he could not have failed to have detected its movement. These early observations of Flamsteed and Lemonnier were of great value in determining the orbit of this new planet.

At opposition Uranus is visible to an unaided eye, appearing as a star of the sixth magnitude. It cannot, however, be recognised unless one is familiar with the heavens and knows exactly where to look for it. Uranus travels about the sun in its orbit once every eighty-four years, thus changing its place in the sky only a little over four (4°) degrees each year. Its synodic period is 369 days, so that oppositions occur only four days later each year. In 1907 this planet came on the meridian at midnight on July 3–4, but, as it was some 23° south of the equator, it did not rise far above the southern horizon. It will be many years before the planet will be favourably situated for observations made in the United States or Europe.

In a telescope Uranus appears as a pale greenish disc, showing a decided ellipticity. By some observers this ellipticity has been estimated as high as $\frac{1}{14}$, and if this be real, it indicates a rapid rotation of the planet. No definite rotation has yet been proved, although many years ago Buffham observed some

faint markings and suggested a rotation in twelve hours. Other observers have glimpsed faint shadings and illusory bands, somewhat similar to the dark belts of Jupiter. So indefinite are these markings, however, that no satisfactory conclusions can be drawn from them.

Neptune was known to exist long before it was ever seen, and its final discovery ranks as the greatest triumph of mathematical astronomy. During the early part of last century, the then recently discovered planet Uranus began to exhibit irregularities of motion, which could not be accounted for, except by the presence of some unknown disturbing body. These deviations of Uranus from its calculated path became in 1845 as great as 2′, a quantity scarcely perceptible to the naked eye, but "intolerable" in any mathematical theory. Two young mathematicians, Le Verrier and Adams, the one in France, the other in England, attacked the problem independently and reached similar conclusions: that these deviations could be fully accounted for by the attraction of a planet outside the orbit of Uranus. The orbit of this hypothetical planet was computed by the two mathematicians and the part of the sky in which it should be located was pointed out. Adams's results were communicated to the then Astronomer Royal, Airy, and Le Verrier's to the Paris Academy of Sciences; Adams's antedating Leverrier's by a few months.

After some delay Challis, at Cambridge Observatory, began a systematic search for the unknown

body, laboriously observing every star within a space 10° wide by 30° long. The only sure way to detect the planet was by its motion and, therefore, Challis decided to map the position of every star within this zone on three separate nights. He began his work on July 20, 1846, and in the next few weeks measured over 3000 stars, and began the comparison and reduction of his observations. Meanwhile Le Verrier wrote to Encke at Berlin, where there had just been completed a map of that part of the sky in which the planet was supposed to be located. On the very night that Le Verrier's letter was received, September 23, 1846, the search was begun and Galle found an object which was not on the map. The following evening the object was reobserved, and as it had shifted its place its true character as a planet was confirmed. The actual planet was found less than 1° from the theoretical place assigned by Le Verrier.

Upon reducing his observations Challis found that he had actually seen the planet on two occasions, July 30th and August 12th. Had he, therefore, reduced and compared his observations day by day, the planet would have been discovered some weeks earlier and Adams and Challis would have had the honour which now belongs to Le Verrier and Galle.

Neptune, as this new planet is called, is some twenty-eight hundred millions of miles from the sun and requires one hundred and sixty-four (164) years to complete one revolution in its immense orbit. During the sixty-one years that have elapsed since

its discovery, it has passed over but little more than one third of its path. It is invisible to the unaided eye, but appears in a telescope about as bright as an eighth magnitude star, showing, however, a distinct disc. It is so far distant that practically no surface details can be detected. Yet through the curious motion of its satellite, it can be proved that the planet must have a decidedly elliptical figure, and that it is most probably in very rapid rotation.

For a number of years Neptune will be in opposition during the month of January in each year and will be very favourably situated for observation, crossing the meridian high up toward the zenith.

CHAPTER XII

SATELLITE SYSTEMS

FOUR of the planets are each accompanied by two or more satellites, and thus form solar systems in miniature. Two planets have each a single moon, and two, Mercury and Venus, are unattended. In all there are twenty-five (25) known satellites, and of these all but the moon are telescopic bodies and were unknown and undreamed of until Galileo turned his toy towards the skies and discovered the Medicean stars. These, the four larger satellites of Jupiter, were thus the first heavenly bodies ever discovered, the first fruits of the modern spirit of patient scientific research and experiment.

Of the twenty-five satellites, the earth has one, Mars two, Jupiter seven, Saturn ten, Uranus four, and strangely enough Neptune only one. Thus the number of satellites attending each planet increases regularly with the planets remoteness from the sun, until Uranus is reached. Uranus and Neptune are so far distant, however, that their attendant moons are seen with difficulty and there may well be other satellites which have as yet escaped detection. Only within the last few years have new satellites of

Jupiter and Saturn been found and the all-penetrating photographic plate may yet reveal many more attendants to the outer members of the sun's family.

Satellites of Mars. The two satellites of Mars were first seen by Hall in August, 1877, with the aid of the great 26-inch telescope of the Naval Observatory at Washington. These bodies are extremely small and faint and can be observed only when Mars is near opposition. So small are they that their diameters cannot be measured; only from the amount of light which they reflect can estimates of their dimensions be made. Assuming that their surfaces have the same reflecting power as the planet, Pickering has found their diameters to be not far from six miles. With the possible exception of some few of the fainter asteroids, these moons of Mars are the smallest known bodies of the solar system.

The discovery of these satellites furnished a remarkable confirmation of one of the wildest flights of the human imagination. In 1726 Swift published his biting satire, *Gulliver's Travels,* and in the voyage to Laputa he ridiculed the science of his day. Astronomy and astronomers received their full share of the ridicule; the Laputan astronomers were pictured as far in advance of those of Europe. Among their achievements Swift chronicled the discovery of "two lesser stars, or *Satellites,* which revolve about *Mars,* whereof the innermost is distant from the Centre of the primary Planet exactly three of the Diameters, and the outermost five; the former revolves in the

space of ten Hours, and the latter in twenty-one and a half." When the real satellites were found by Hall a century and a half later, they were found to be distant from the planet three (2.7) and seven (6.9) radii and to revolve about Mars in periods of seven and a half and thirty hours respectively.

Hall gave to these minute bodies the names of the mythological attendants of Mars, the God of War, "Deimos" and "Phobos" (Fear and Panic). Phobos, the inner satellite, is the larger and is unique in the solar system. Its period, or month, is the shortest known and is less than half the length of a Martian day. This is the only case known of a satellite revolving in its orbit faster than its primary rotates. On account of this rapid flight, Phobos passes over the surface of the planet from *west to east;* to an inhabitant on Mars (if there be any) Phobos would appear to rise in the west and, after the lapse of a little over five hours, set in the east.

Deimos also exhibits noticeable peculiarities. It rises in the east and sets in the west like any well regulated moon, but its motion across the heavens is exceedingly slow. Mars rotates on its axis in 24 hours and 37 minutes, while Deimos takes only 30 hours and 18 minutes to complete its orbit. If these two periods were identical then Deimos would continually hover over the same part of the Martian surface. As the period of Deimos is slightly the longer, that body will appear to travel slowly toward the west but will remain above the horizon for several days.

During this time it will go through all its changes of phase, so that to a Martian is presented the curious spectacle of a moon hanging nearly stationary in the sky, waxing and waning, and passing from new to full.

Satellites of Jupiter. Four of Jupiter's satellites were discovered by Galileo and these may be seen with the aid of a good field or marine glass. They are so bright that, were it not for the dazzling brilliancy of Jupiter, they could be seen by the unaided eye. In fact there are some doubtful records of these Medicean stars having been so observed and it is not impossible that one or more of them might be glimpsed by one of extremely keen vision. During the century immediately following Galileo's discovery several additional satellites were claimed for the giant planet, but in every case these reputed moons lacked the one essential of being real. One of these cases is of more than passing interest on account of its being probably one of the first astronomical observations made in this country. On August 6, 1664 (old style), John Winthrop, Jr., at Hartford, observed a supposed fifth satellite and he later communicated the fact to the Royal Society. His telescope was a reflector of "but 3 foote and halfe with a concave ey-glass," yet the five satellites were distinctly seen and Winthrop could discern no reason for believing the fifth body to be "some fixt starr with which Jupiter might at that tyme be in neare conjunction." However Winthrop's satellite was not

again seen and a careful investigation of the records a few years ago showed that he had been misled by "a fixt starr in neare conjunction." A few years later, in 1671–1672, Winthrop was engaged in making astronomical observations at Harvard College, and thus began the scientific record which has made that institution famous in the annals of astronomy.

After clearly proving the non-existence of several such pseudo-satellites, astronomers were firmly convinced that Jupiter had but four attendants, the four originally discovered by Galileo. Great was the surprise, therefore, when in 1892 Barnard announced the discovery of a fifth. This satellite—for its existence has been amply confirmed—revolves about the planet in a much smaller orbit than do any of the other four. So close to the planet is it, that only through some three or four of the largest telescopes can it ever be seen. In visibility it is the most difficult object in the solar system and it can be observed only by screening off the glare from Jupiter. It has no connection with any of the early pseudo-discoveries and could not have been seen through any of the telescopes then in existence. The discovery of such a faint and difficult body was a triumph for the great Lick telescope and also for the most careful, thorough, and reliable observer of recent times.

Still more recently, in 1905, two more satellites have been added to Jupiter's system. These, known as the sixth (VI) and seventh (VII), were found by Perrine by the aid of photography. They are extremely

small and are at a great distance from the planet. So remote are they that it takes them some 265 days to complete their orbits about Jupiter. Thus their months are longer than the years of Mercury and of Venus, and more than eight times the length of our lunar month.

The original four satellites are now commonly known as the first (I), the second (II), the third (III), and the fourth (IV), the numbers indicating their relative distances from the planet. Special names have been assigned to them and are still sometimes used; these names are Io, Europa, Ganymede, and Calypso. Their orbits range in size from six to twenty-four radii of the planet, or from 260,000 to 1,170,000 miles; their periodic times, or months, range from 1 day and 18 hours for Io to 16 days and 16 hours for Calypso. During their passage around Jupiter these bodies present many curious and interesting phenomena. Their orbits are all nearly circular and lie in the plane of Jupiter's equator, which differs but little from the plane in which that planet travels about the sun. As the axis of Jupiter's shadow lies in the plane of the orbit, the satellites will, therefore, pass within the shadow and be eclipsed. The first three satellites are eclipsed at every revolution. but the fourth sometimes passes either above or below the shadow, just as our moon usually passes above or below the shadow of the earth.

These eclipses are interesting to watch and they led to the discovery of the velocity with which light is

propagated through space. At one time they were also used as an aid to navigation. An eclipse of one or the other of these satellites must occur at intervals of less than two days, and the exact Greenwich times at which they occur can be calculated in advance and tabulated in the Nautical Almanacs. The captain of a whaling ship on a long voyage, or an explorer in inaccessible regions, can thus always find the Greenwich time by observing an eclipse with a small telescope or strong marine glass. Thus the rate of a chronometer can be checked, or it can even be set in case of stoppage. Unfortunately, however, for the accuracy and usefulness of this method, the time at which an eclipse occurs cannot be determined with exactness. The satellites are bodies of considerable size and they enter the shadow gradually; they fade slowly from sight and the exact instant of the eclipse cannot be observed within many seconds. Now four seconds correspond to one minute of arc, or to one nautical mile at the equator. An error of one minute in determining the time of an eclipse, would, therefore, cause a error of fifteen miles in determining a ship's longitude.

The satellites frequently pass between the earth and Jupiter and then appear to cross, or transit, the disc of the planet. At times also the shadow of a satellite is cast upon the face of the planet and appears like a black body crossing the disc. Some curious observations have been made while the satellites were in transit. Barnard saw the first satellite

apparently change its shape as it transited the light and dark portions of the planet. When seen against a dark belt the equatorial diameter of the satellite appeared much the longer; when projected upon the bright surface of the planet, the polar diameter appeared the longer, and sometimes the satellite even appeared double. Barnard interpreted these appearances as being due to bright and dark belts upon the satellite; the polar regions being dark, and the equatorial bright.

Various markings have also been observed on Satellites III and IV. Equatorial belts and bands have been seen by Schaeberle and Campbell and by Pickering and Douglass, while Barnard noted the presence of white polar caps, somewhat similar in appearance to those on Mars. These two bodies are full sized planets, III being 3560 miles and IV 3350 miles in diameter. They are both considerably larger than Mercury and only slightly smaller than Mars.

Satellites of Saturn. In addition to the innumerable bodies that form the rings, Saturn has a greater number of known satellites than any other body of the solar system. Titan, the largest and the first known, was discovered by Huyghens in 1655. Within the next thirty years Cassini discovered four more satellites, and nearly a century later Herschel added two members to Saturn's family. The eighth and last satellite to be visually discovered was found by Bond at Harvard in 1848.

In 1899 while examining photographs taken the previous year at Arequipa, W. H. Pickering noted a star which seemed to move about Saturn. Although far beyond the outermost known satellite Pickering deemed this a new member of the solar system and named it Phœbe. For several years this body was lost among the countless faint stars of the Milky Way, but was again found on plates taken on August 8, 1904. Since that date it has been repeatedly photographed and Barnard has directly observed it with the Yerkes telescope. On April 29, 1905, Pickering found still another satellite, this making the tenth known attendant of Saturn. The extreme difficulty of observing these minute bodies may be shown by a terrestrial comparison. To see Phœbe at a distance of nearly nine hundred million miles is the equivalent of standing in New York City and watching the flight of a small humming-bird as it darts hither and thither over the flower beds in front of the Capitol at Washington.

These ten satellites vary greatly in size and in their respective distances from Saturn. Phœbe, the smallest, is some 42 miles in diameter. Titan, the largest, is 3000 miles in diameter, about the same size as the planet Mercury. Mimas is but three radii (117,000 miles) of Saturn distant and revolves about that planet in 22 hours and 37 minutes; Phœbe is some 200 radii (7,996,000 miles) distant and requires more than 546 days to complete its orbit. This, the longest period of any satellite, is more than a year

and a half, more than six times the period required for Mercury to complete its orbit about the sun.

The satellites seem to form three groups. The five inner ones are all comparatively near the planet, their distances ranging from 117,000 to 332,000 miles. These bodies also are somewhat of the same size; Mimas, the smallest of the group, is some 600 miles in diameter, while Rhea, the largest, is but 1500 miles. Separated from this group by a broad gap there is a second group of three satellites,—the sixth (VI), tenth (X), and seventh (VII), whose distances range from 770,000 to 934,000 miles. The individuals of this group, however, vary greatly in size; Titan is over 3000 miles in diameter, while Themis is very minute. Far out beyond these three lie the orbits of the third group, Japetus and Phœbe, whose distances are, respectively, 2¼ and 8 million miles.

The motions of these ten satellites present many curious problems in celestial mechanics. The orbit of Titan is nearly circular, while that of Hyperion is very eccentric. These two bodies are so related that the longer axis of Hyperion's orbit is carried around once in nineteen years in such a manner that the conjunctions of the two satellites always occur where the distance between the two orbits is the greatest. All of the two inner groups of satellites have their orbits in the same plane, the plane of the rings. Japetus and Phœbe, however, travel in inclined planes.

The motion of this latter satellite is most peculiar—

it retrogrades, or travels about Saturn in a direction opposite to that in which all the planets move. It will be remembered that the sun and the planets all rotate upon their axes and the planets all revolve about the sun in the same direction, from west to east. This ninth moon of Saturn breaks this rule and revolves from east to west. Somewhat similar are the motions of the four satellites of Uranus and of the single attendant of Neptune.

The Satellites of Uranus. Two of these four bodies were discovered by Herschel in 1787, and two by Lassell in 1851. Their distances from Uranus vary from 120,000 to 360,000 miles and their periods from 2.5 to 13.5 days. They are all comparatively small bodies, less than 1000 miles in diameter.

The remarkable feature of this system is that the four bodies all move sensibly in the same plane and this plane is inclined 98° to the planet's orbit. With the exception of a few comets all other bodies of the solar system travel in planes but slightly inclined to the ecliptic, whilst the orbits of these four moons are practically perpendicular to that plane. In this plane the satellites revolve about Uranus in the retrograde direction.

On account of the great inclination of their orbital plane there are times when the orbits are seen in their full size and shape, and the satellites may be watched as they revolve around and around Uranus in circles. Once every forty-two (42) years, however, the position of Uranus will be such that this orbital plane

passes through the sun, and will be seen, from the earth, edge on. At these times the satellites will seem to oscillate up and down in straight lines, appearing first north and then south of the planet. The last time this occurred was in 1882, and the next will be in 1924. In 1903 Uranus was in the most favourable position for observing the satellites.

The Satellite of Neptune. So far as known Neptune has but one satellite, which was discovered by Lassell in 1846 within a month after the discovery of the planet itself. This body, which as yet has received no name, is approximately the size of our moon and is at about the same distance from Neptune that the moon is from the earth. Owing, however to the great mass of Neptune as compared with the earth, this nameless satellite revolves in its orbit at a much greater speed than does our moon; the length of a Neptunian month is a trifle less than six days.

The striking feature in connection with this satellite and that which for many years gave it a unique place among the bodies of the solar system, is that it moves around Neptune from the east toward the west, it moves backwards or retrogrades. This distinction is now shared by the ninth satellite of Saturn and possibly also by the seventh moon of Jupiter. The satellites of Uranus can hardly be said to retrograde for they move more nearly north and south in a plane nearly perpendicular to the orbit of the planet.

The orbit of this satellite is slowly changing its

position in a manner which cannot be accounted for unless the equatorial diameter of Neptune markedly exceed the polar. This peculiar shifting of the satellite's orbit indicates that Neptune, like the earth, has a decided equatorial bulge and this in turn leads us to infer a rapid rotation for that planet. Thus from the motions of the satellite astronomers may yet be able to locate the position of the poles and the equator of the planet and to determine its period of rotation.

CHAPTER XIII

COMETS AND METEORS

IN the astronomy of the ancients comets had no position; in the great text-book of Ptolemy they are not even mentioned. Toward the middle of the Christian Era we find their nature discussed, but they were universally regarded as belonging to the atmosphere and not as astronomical bodies. The appearance of one of these "hairy stars" has always been the cause of wonder and of dread. And the ludicrous excitement and apprehension is as wide-spread to-day as it was in 1572 when George Busch, a German, spoke of Tycho's new star as a comet and claimed that it was caused by the burning of human sins and wickedness in the upper part of the air, and that the burning ashes from it fell upon the heads of men and caused all kinds of disease and pestilence, even Frenchmen! Within the last few years, in this country, people have been driven insane by the newspaper excitement over a body they could not see; and in the "black districts" of the South the more credulous people prepared their ascension robes and waited in fear and trembling for the end of the world.

In appearance these bodies vary widely: some are

the most magnificent objects in the heavens, stretching in great brilliant curves across the sky; others are faint hazy patches of light never visible except in the most powerful of telescopes. Of the 800 or so comets which we have on our records, some 400 were observed before the invention of the telescope in 1610 and were, therefore, bright objects visible to the unaided eye. Of the 400 observed since that date, a very small number—some 70 or 80 only—have been visible without the aid of a telescope. The great majority of the comets now on our lists would never have been seen or known of had the telescope not been invented. During the last century out of 300 known comets, only 13 were visible to the unaided eye; the last brilliant and conspicuous comet was that of 1882.

If a comet be examined with a spectroscope the light given off is found to be partly reflected sunlight and partly original with the comet itself. A comet is, therefore, a self-luminous body, and it has been shown that sodium, magnesium, and iron form a large part of the mass of these bodies.

There have been many theories as to the exact nature of comets; that most generally accepted is that comets are "sand-banks"; that is, that they consist of small particles widely separated: particles varying in size from pinheads to small rocks and separated by many hundreds of feet. These particles are surrounded and immersed in masses of gas. Furthermore, the mass of a comet is very small, the volume very large. Take the great comet of 1882,

for example; including its tail, its volume was more than eight thousand times that of the sun; more than ten thousand million times the size of the earth. With its head completely enveloping the earth and moon its tail would have rested on the sun. The smallest telescopic comets have diameters five or six times that of the earth.

On the other hand, in all the space occupied by these strange bodies there is very little matter. This has been repeatedly shown. Comets have passed and re-passed the earth at very close quarters without the least apparent effect on the earth. Attraction is mutual; if a comet pass near a body of the solar system, the motions of both must be disturbed, but as is always the case the smaller body suffers the greater injury. Lexell's comet of 1770 passed so close to the earth that its period was changed by days. Had this comet contained $\frac{1}{100,000}$ as much matter as the earth does, then our year would have been lengthened by some seconds of time. Several other comets have passed even closer to the earth and have been greatly disturbed in their paths; but during all this time the length of our year has not been altered a single second. We know, therefore, that the amount of matter contained in these comets must be less than $\frac{1}{100,000}$ part of the earth; an amount of matter which is comparable with the mass of the earth's atmosphere. Professor Pierce came to the conclusion that the matter near the head of an ordinary comet is about equivalent to a ball of iron one hundred miles in di-

ameter. A comet cannot be weighed and the amount of matter it contains determined with exactness, but it is known that the mass of one of these bodies is extremely small when compared with any other body of the solar system.

Now this minute quantity of matter is spread out through an immense part of space; the average density of such a body must therefore be excessively small, about $\frac{1}{7000}$ that of the air at the earth's surface. No vacuum can be produced in the laboratory that approaches this. The above is the mean density; near the head of the comet, however, it is probably much greater and near the extremities of the tail much less. It has been said that if an ordinary telescopic comet of fifty or one hundred thousand miles in diameter could be brought into a laboratory, it could be condensed and packed away in a pill-box and comfortably carried around in one's pocket.

It has been noted that some of the light from a comet originates in that body. Lockyer suggests that this light is produced by collisions between the solid masses that form the bulk of the comet. According to his ideas a comet consists of a swarm of meteoric stones, all being originally cold and dark. As the swarm travels round the sun, numerous collisions take place, the temperature is raised, the particles vaporised and finally rendered incandescent. Some of the light may indeed be derived from this cause. Electrical discharges through the constituent particles are also a possible cause of the light.

Nearly all the large and brilliant comets have been accompanied by long tails. Donati's comet of 1858 probably had the most symmetrical and beautiful tail of any of the recent comets. The great comet of 1882 also possessed a remarkably splendid tail. The marked peculiarity of the tails of all comets is that they are turned away from the sun as though acted upon by some repelling force. The tail is not in a straight line connecting the sun and the head, but along a curve convex to the direction of the comet's motion. The tail is an emanation, not an appendage: the particles that form the tail are ever changing—the appearance is continuous but the matter varies from time to time. The researches of Bessel and other eminent astronomers show that the supposition of a repellent action of the sun on the particles composing the tail fully accounts for the details observed and agrees with the observed position and size of the tail in the various positions of the orbit. There have been many suppositions and theories as to the nature of this repellent force which counteracts gravitation. It has been suggested that this repulsive force is electrical, and in the last few years Arrhenius has suggested that it is the "light pressure" on the minute particles of gas forming the body of the comet.

The theory that the repulsive force is due to electrical action was first suggested by Olbers and was afterwards developed in detail by Bredichin. From measures of many comets' tails he found them to be

Photographed by Barnard.

Fig. 31. Daniel's Comet of 1907.

of different types: the straight, or hydrogen, tail; the ordinary curved tail of the hydrocarbons, and the short stubby tails of metallic vapours. The repulsive forces in these different types are respectively 18.5, 3.2, 2.0, and 1.5 times the attraction of gravitation. There are many difficulties in the way of explaining this repulsion by electrical action, and the latest investigations of Lebedew and others indicate serious physical objections to the entire electrical theory.

No such theoretical objections can be raised against the light pressure theory as urged by Arrhenius. Light is sent out from the sun in waves and it can be shown that when light strikes against an object it produces a pressure. When the waves of the sea break against a beach they tend to drive the pebbles and sand upward along the beach. Now the waves of light are extremely small and are measured by the millionths of inches, and when they break against ordinary-size particles of matter the pressure they produce is so infinitesimal as to cause no material effect; but when they break against and strike particles of matter which are of the same relative size as themselves they drive those particles along with them just as an ocean wave picks up a chip and carries it along. The action of "light pressure" will fully and in a satisfactory manner explain the tails of the comets.[1]

[1] "Comet Borrelly and Light Pressure," S. A. Mitchel, *Astr.-Physical Journal*, vol. xx., No. 11.

Whatever be the nature of the repulsive force there is no question that particles are driven out from the head of the comet and are left behind as it passes on its way. This action becomes more and more marked and stronger the closer the comet approaches the sun. The comet thus is continually losing a part of itself, it is certainly wearing away and being spread out and scattered along its path. A short-period comet, one that returns to the sun every five or six years, will, therefore, be but short lived. Biela's comet is a notable example of this—first seen in 1826, it was found to be travelling in a six-year period; it continued to be regularly visible until 1852, by which time it had become completely disintegrated.

So much for our knowledge in regard to the physical condition of these strange bodies: each is a swarm of minute particles surrounded with gas, and the swarm is constantly being dissipated through space. But where do they come from; are they mere visitors to the solar system, or are they part and parcel of our little universe, are they messengers from outside space, from the distant suns, or are they the mere flotsam and jetsam, the debris left over or thrown aside in the making of our sun and the earth and the planets?

Until very recent times comets were thought to be transient visitors to the solar system. Of the eight hundred comets which have been seen and recorded since the shepherds watched the stars from the fields of Chaldea, only forty or fifty appear at first sight

to be members of our system; the great majority of these bodies are seen but once and then disappear. Thus they have been considered as true wanderers, travelling through space, drifting hither and thither, just as the sun, with its attendant retinue of planets, is moving onward in some unknown path. When the paths of the sun and such a free comet approach, the attraction of the sun is to the comet like the flame to the moth; the comet flutters for a moment about the sun, and passes on its way. But not unscathed; like the moth, the comet has been singed; the fierce light of the sun has beaten upon it and spread out its particles and scattered them along its path.

This idea that comets originate outside the solar system rests upon the supposed character of their orbits. The great majority of these strange bodies appear to travel in parabolas, open curves leading from infinite space to and around the sun and thence back into the region of the fixed stars. Sir Isaac Newton first showed the possibility of comets moving in such paths, and the prestige of his name and the ease and facility with which parabolic orbits can be calculated led to the adoption of this curve as representing the motions of these bodies. Under the law of gravitation a body may travel about the sun in any one of the three conic sections, or curves, known as the ellipse, the parabola, and the hyperbola. That is, if there were in the universe but two bodies, the sun and a comet, then would the comet describe about the sun one of these three mathematical curves, the

exact character and size of the curve depending solely upon the speed of the comet relative to the sun at the beginning of time. But the instant a third body is added to the system this is no longer true. The parabola is a limiting curve, is what might be called a curve of " unstable " motion. To describe a parabola about the sun, a body must have at each point of its path a certain definite velocity. If this parabolic velocity be changed by the slightest amount the path ceases at once to be a parabola; if through any cause the velocity be decreased the path becomes an ellipse, if increased an hyperbola. Now if a comet start in a parabolic orbit, it cannot continue for a single instant in that path, for it must of necessity be attracted by Jupiter, by Saturn, or by some or all of the planets, and such attraction will either increase or decrease its speed. Thus a parabolic orbit is a physical impossibility.

Yet to-day the greater number of newly discovered comets are classed as parabolic, and their orbits are computed and given as parabolas. This is because a very small part of the actual orbit is seen, such a small part that it is impossible to determine the exact character of the real path. Near perihelion the difference between an elliptic orbit of great eccentricity and a parabolic orbit is so slight as to be inappreciable. On the other hand the labour of keeping track of a body moving in a very eccentric elliptic orbit is many, many times greater than that required to keep track of a body moving in the corresponding

parabola. Parabolic orbits are thus computers' fictions, approximate paths assumed for the purpose of lessening labour.

The real paths of comets must be either ellipses or hyperbolas. Ellipses if they are part and parcel of the solar system; ellipses or hyperbolas if they are visitors from outside space. But of all the comets whose orbits have been determined, not one is clearly and conclusively hyperbolic. Several are classed as such, but the eccentricities of the computed orbits differ but little from unity, and these orbits represent the observations but little better than the corresponding parabolas. On the other hand there are many orbits which are clearly ellipses, and many more of the so-called parabolic orbits, which lean to the side of the ellipse. These elliptic orbits differ from those of the planets in that the eccentricities are very large, and the comets, therefore, pass out to enormous distances from the sun. Except near perihelion their motion is extremely slow and, with few exceptions, the periods in which they travel their curves are measured by hundreds and by thousands of years.

Thus the real orbits of these bodies are ellipses and accordingly we know they are true members of the solar system, parts of the original nebula or meteoric mass from which the sun and the planets have been gradually evolved.

Some few comets travel in well-defined elliptic orbits of short period and of relatively small

eccentricities. Thirty or more of these have their aphelia near Jupiter's orbit and have periodic times ranging all the way from three (3) to eight (8) years. These form the so-called "Family of Comets" belonging to Jupiter. Neptune is credited with a similar family of six comets and the other major planets with smaller families.

These comets have had their paths made smaller by the action of the planets. Moving originally in an immense ellipse, such a comet as it approaches the sun may chance to pass near one of the greater planets. One of two things must then happen, its speed must be either increased or decreased. If increased its path will be lengthened, if decreased its orbit will be made more distinctly elliptic and its period shortened. Radical changes in cometary orbits have been observed, most notably in the cases of Lexell's comet of 1770, and of the Brooks periodic comet of 1889. Previous to 1886 this latter body was travelling about the sun in an immense ellipse, never passing close enough to the earth to be seen. Around and around went the comet until in the summer of 1886 it passed under the spell of Jupiter's attraction. Its motion was decreased, its path turned into the small seven-year ellipse around which it is now travelling, and at the same time the comet itself was broken into fragments. As it approached the sun in its smaller path it was discovered by Brooks in 1889 and became an object of interest and of study.

The comet remained visible with telescopes of ordinary power until March, 1890, after which date it could be seen with the great Lick telescope only. With this magnificent instrument Barnard followed its path for nearly a year, or until January, 1891. Its path was computed by Bauschinger, Poor, and others, and predictions were made as to where and when it would again be seen. So accurately had the mathematicians calculated its path that when it was rediscovered on June 20, 1896, by Javelle, it was within 7′ of its predicted place; a distance less than one quarter the apparent diameter of the moon. During this second appearance the comet was much fainter than before and was visible for only a few months, disappearing in February, 1897. For a third time the body returned to the vicinity of the earth in the summer of 1903 and remained visible until the following January. It was much fainter than at either of the former appearances and could be seen only with the aid of the largest telescopes.

The future of this body will be as interesting as its past. Unless it become wholly disintegrated by the pulling and hauling of the sun and planets, it will be seen again in 1910, and yet again in 1917. But early in 1921 it will again come into close approach with Jupiter, and beyond that point its history cannot be predicted. This collision will probably end its story, so far as we on the earth are concerned, for it will undoubtedly be still further broken up and its orbit may be so changed that it will never afterwards be seen.

The most brilliant comet since that of 1882 was discovered by Daniel at Princeton early in the morning of June 10, 1907. At this time it was just below the limit of naked eye vision, but it rapidly grew brighter and by July 10th was easily detected with the unaided eye. It drew nearer and nearer the earth until on August 1st it was only some 70,000,000 miles distant, and a most conspicuous object in the eastern sky. It was visible for an hour or two before sunrise, appearing as a hazy disc somewhat larger and brighter than Mars, with a tail stretching nearly twenty-five degrees across the sky. As the moon is but one-half a degree in diameter, the tail of Daniel's comet equalled in length fifty moons placed edge to edge.

The comet remained visible to the naked eye during August, but gradually became fainter and fainter as it moved away from the earth. Figure 31, which shows it at its brightest, is from a photograph taken by Barnard on July 17 with the 10-inch Bruce telescope of the Yerkes Observatory.

Meteors. Under the more familiar name of "Shooting-stars" meteors are known to even the most casual observer of the heavens. On almost any clear, moonless night one or more star-like points of light can be seen to dart through the heavens and disappear. In summer and fall these objects are more numerous and often a score or more may be observed within an hour. Occasionally a meteor of striking brilliancy is seen to pass like a ball of fire across the

sky. The flight of such a body is often accompanied by loud explosions and a continuous thunder-like rumble. Several have been seen to strike the earth and many meteoric fragments are to be found in museum collections. The American Museum of Natural History in New York has a superb collection, among which is to be found the largest known meteorite. This is the famous "Aghnito," a huge mass of meteoric iron weighing 37½ tons. This was found in the ice fields of the Esquimaux and brought from Greenland by Lieut. Robert E. Peary.

These meteorites are composed of stone mixed with metallic iron, or iron compounds. They contain many elements that are found on the earth, iron and nickel being the most frequent metals; yet not a single unknown element has been found. So far as the mere matter which they contain, each and every meteorite might well be a portion of our own world. The form in which that matter appears in the meteorite differs, however, considerably from that in which the same substance appears on the earth. They show peculiar crystals unlike any terrestrial formation. Some slight resemblance, indeed, has been drawn between meteorites and the lava from deep volcanoes.

The ordinary shooting-star or meteor is a small body rendered incandescent by its rapid flight through our atmosphere. By two observers, stationed several miles apart, making simultaneous observations, the actual path of a meteor can be

determined. Many such observations have been made and the paths of these bodies located at various altitudes between 50 and 100 miles. They are rarely visible for more than a second and during this brief time they travel some 40 or 50 miles at speeds of 10, 20, or even 40 miles per second. To the atmospheric friction caused by this speedy flight are due the heat and light of these minute bodies.

When a moving body is stopped its energy of motion is transformed into heat. If a body moving at the rate of 100 yards per second be brought to rest enough heat will be produced to raise the temperature of an equivalent mass of water one degree centigrade. The amount of energy in a moving body is proportional to the square of its velocity, and as there are 1760 yards in a mile, a body moving at the rate of one mile per second will produce 310 times (17.6^2) as much heat as a body moving 100 yards per second; while a body moving at a speed of 20 miles per second will produce 124,000 times as much heat. That is, if a meteor moving at the average speed of 20 miles per second, have its velocity destroyed, it will produce sufficient heat to raise its temperature 124,000° centigrade, provided its specific heat be the same as water.

This heat is developed along the meteor's path and a large portion of it is communicated to the surrounding air. The heating effect upon the meteor is mostly confined to the surface, which is fused and melted, and swept off by the rush of the air. Thus

the surface of a large meteor may be rendered incandescent, while the interior remains intensely cold.

The number of meteors or shooting-stars is very great. While a single observer can see but few on any given night, yet it has been computed that several millions pass into the atmosphere on each and every day. As a rule these bodies are extremely minute, hardly more than small pebbles or particles of dust. From the length of its path, and the brightness of a meteor, the total amount of light given off can be calculated. But this light and heat is derived from the energy of the moving body, which depends upon its mass and velocity. The velocity is known and hence the mass can be calculated. The computations can only be approximate, it is true, but they are sufficient to establish clearly the small size of the average meteor,—a body no larger than the head of a pin.

These bodies are consumed and dissolved away in the upper regions of the atmosphere. As fine dust they gradually settle down through the air and are finally scattered over the earth's surface. Occasionally the body is so large and solid that it cannot be completely dissolved by its passage through the atmosphere. In this case the meteor falls to the earth and the meteoric stone finds a final resting-place in some museum.

It is well known that at certain seasons of the year meteors are more frequent than at others. In the middle of August, toward the middle of November,

and again near the last of November many meteors are to be seen. The August meteors last for about a week and they all appear to originate in the constellation Perseus, and are for this reason called the Perseids. If, on an August evening, the path of each meteor be marked upon a chart of the heavens, and these paths traced backward, then all the paths will be found to intersect in the so-called *radiant point* in Perseus. The meteors are travelling through our atmosphere in parellel lines and all parallel lines seem to vanish in a common point, just as when one stands in the middle of a straight stretch of railroad track the rails and the telegraph wires all seem to meet in a common point some miles away. The radiant point of meteoric showers is the vanishing point of perspective.

The meteors which appear yearly about November 15th have their radiant point in Leo and are called Leonids. Those which appear about the 24th of the month radiate from Andromeda and are called Andromids. These two showers vary greatly from year to year. In 1833 and in 1866 great showers of Leonids occurred. The number that were seen during the early morning hours of November 12, 1833, were estimated by the millions; they appeared like snow flakes in a heavy storm. The shower of 1866, though still brilliant, was less remarkable. Again some thirty-three years later, in 1898 and 1901, the Leonids were much more numerous than usual. Historic research shows that for some thirteen cen-

turies these noticeable showers have occurred at regular intervals of some thirty-three or thirty-four years.

This periodic return of the showers indicates that the meteors form a great group or swarm which revolves about the sun in $33\frac{1}{4}$ years. The path which this meteor swarm travels intersects the orbit of the earth at the point where our planet is to be found toward the middle of November. From this period and from the exact position of the radiant point at each shower it is possible to compute the orbit in which these bodies are travelling. This orbit was found shortly after the display of 1866 and Schiaparelli pointed out that it was almost identical with the orbit of Temple's comet of 1866. The meteors were found to be following the track of the comet, to be, as it were, an invisible part of that body.

Similar investigations show that the August meteors move in the same orbit as did Tuttle's comet of 1862, and that the Andromids travel about the sun in the ellipse which was formerly the orbit of Biela's comet.

These coincidences led to the great modern discovery in regard to meteors; to the conclusion that they are the disintegrated parts, the debris of comets. The action of the sun and of the planets breaks up and dissipates the dense cometary swarm, and scatters its particles along its path. These particles continue to travel about the sun and follow each

other in nearly parallel orbits. The thousands of comets, which have travelled about the sun, have each and all left fragments to mark their respective paths, and these fragments the earth picks up in the form of meteors.

The idea that the vast spaces between the sun and the various planets are void and untenanted now belongs only to the history of science. To-day it is known that these spaces are filled with vast swarms of minute, dust-like bodies, each and every one revolving about the sun in vast ellipses, each one being in fact a microscopic planet. These bodies make their presence known not only as meteors or shooting-stars, but also by their power to reflect sunlight and thus produce the peculiar evening glow of the Zodiacal Light. This is a soft, faint light seen in the western sky for an hour or more after sunset. This glow is to be seen only on clear, dark nights, and the smoke and glare of a great city render it invisible.

CHAPTER XIV

THE EVOLUTION OF THE SOLAR SYSTEM

IT is universally recognised that the solar system is in process of a gradual evolution, that in the past it was, and in the future it will be, radically different from what it is to-day. The sun, the earth, and the planets were not made as they now are, they grew and developed. Ages ago the earth and moon were one; together they formed a single hot, plastic globe incapable of supporting life; to-day the earth is in its prime, while the moon is already cold and dead. Nor is the present condition of the earth the final stage; it is slowly losing its heat and its water, it is gradually growing old, and in some future age will cease to support life and will become like the moon, a cold, lifeless body.

The general idea of the growth and evolution of the solar system was advanced by Kant over a hundred and fifty years ago. But as he was neither a mathematician nor an astronomer his work attracted little attention. In 1796, however, Laplace published a popular treatise on astronomy and in this advanced, in a cautious and tentative manner, his ideas on the development of the solar system and laid the

foundations of the justly celebrated "nebular hypothesis." While not essentially different from the theories of Kant, his ideas were worked out in detail and accorded well with the astronomical and physical data of that time. His work was entirely independent of Kant's and there is no evidence to show that he had ever even heard of earlier writings of this great philosopher.

Briefly stated, Laplace's theory was that the sun and planets were evolved from a vast nebulous mass, intensely hot, and originally extending far beyond the orbit of the farthest planet. This nebula, under the action of its own gravitation, assumed a globular form and a rotation about an axis approximately perpendicular to the plane of the ecliptic. As this nebulous mass cooled it contracted, and as it grew smaller and smaller the velocity of its rotation became greater, this increase in the speed being a necessary consequence of certain fundamental laws of mechanics. With this greater speed of rotation the nebula gradually became flattened at the poles and bulged out at the equator. Finally the rotation became so rapid that the centrifugal force at the equator was equal to the attraction, and as a result a ring of nebulous matter was abandoned. The central body continued to contract and the whole mass assumed the form of a much flattened Saturn surrounded by a nebulous ring. A series of rings was thus abandoned, each ring ultimately breaking up and the material in it collected into a single globe, or

planet. The planet thus formed continued to revolve about the central mass and became in itself a similar contracting nebula; it likewise threw off rings and gave birth to a system of satellites.

This theory of the order and way in which the solar system developed explained completely all the facts known to Laplace and his immediate successors. It was generally accepted in its entirety and greatly affected the scientific thought of the last century. According to the unmodified nebular hypothesis, the outermost planet, Neptune must be the oldest and Mercury the youngest member of the sun's family; and the sun, the planets, and their satellites must all revolve in the same direction and in practically the same plane. At the time Laplace elaborated his hypothesis, nothing was known as to the physical conditions of the various planets and there was no way of judging whether Mercury or Jupiter was the older.

During the century which has passed since the nebular hypothesis was first given to the world, much has been learned concerning the present condition of the solar system, and many facts have been developed which tend to establish the broad underlying idea of planetary evolution. But at the same time many of the details of the Laplacian hypothesis cannot be reconciled with all the later discoveries. The planets all rotate upon their axes and revolve in their orbits about the sun in the same direction as the sun itself rotates, and with but one or two exceptions all the

twenty-five known satellites revolve also in the same direction. These facts tend to substantiate the general correctness of Laplace's views. Again, the sun is now known to be a gradually contracting body; the maintenance of its light and heat is largely due to its slow and steady shrinkage. Based upon the firmly established laws which govern the action of all gases, this contraction theory of the sun's heat shows clearly that this body was in ages past vastly larger than it is at present; shows that it must have filled much of the space now occupied by the numerous bodies of the solar system, and to this extent therefore modern observations confirm the broad features of the nebular hypothesis.

On the other hand the rapid revolution of Phobos about Mars cannot be explained by the simple Laplacian hypothesis. According to this theory the central solar nebula and each subsidiary planetary nebula rotated more and more rapidly as it grew smaller and smaller. Thus the period of rotation of each planet would of necessity be shorter than the periods of revolution of its satellites. Yet Phobos revolves about Mars in less than one third the time it takes Mars to rotate once upon its axis. This anomaly Darwin explains by the aid of tidal friction. He conceives of Mars as having originally rotated much more rapidly, of a Martian day shorter than the present period of Phobos. The action of the solar tides upon the then plastic planet retarded its speed of rotation and lengthened the day, until after

the lapse of ages the present anomalous condition was gradually evolved.

The inner portions of Saturn's ring similarly revolve more rapidly than the planet rotates. This can also be explained as due to tidal friction, but as Saturn is some six times as far from the sun as Mars, the solar tides are much smaller, and tidal evolution must have proceeded far more slowly than in the Martian system. In fact it can be shown that if tidal friction is the cause of Saturn's rotating more slowly than the inner portions of the ring, then must Saturn be some three thousand times as old as Mars.

This is difficult to believe. From what we know of the present physical condition of these two bodies it would appear as though Mars is as old, if not older, than Saturn. Mars is a dead or dying world, is a cold, dark body with but little, if any, water; surrounded by a thin and tenuous atmosphere. Saturn is a world in the making, is an intensely hot body surrounded and enveloped by immense masses of seething vapours. Although Saturn is far larger than Mars and contains nearly nine hundred times as much matter, and would, therefore, cool much more slowly than the smaller planet, yet it would hardly seem as if there could be the great disparity in their ages required by the slow action of tidal friction.

The satellites of Uranus revolve in a plane nearly perpendicular to the plane of the planet's orbit and revolve in that plane in the retrograde direction; the single satellite of Neptune retrogrades, so also does

the ninth satellite of Saturn. These are present-day details of the solar system which cannot be accounted for by the simple nebular theory of Laplace. Darwin and his followers explain these apparent anomalies by the agency of tidal friction. But, while tidal friction has undoubtedly played a marked part in the evolution of the solar system, yet there are limits to its potency. Tidal friction cannot explain in a satisfactory manner the retrograde motion of the ninth satellite of Saturn, as contrasted to the direct or forward motion of all the other satellites of the Saturnian system.

Chamberlin and Moulton, in a recent and most thorough examination of the Laplacian theory, as modified by tidal friction, reach the conclusion that our system could not have been evolved in the manner indicated by Laplace. They find serious mechanical and physical difficulties in the central idea of Laplace that the planets were evolved from concentric rings cast off by the shrinking sun. If the matter now contained in the sun and planets ever formed a nebula extending out to and filling the space within Neptune's orbit, then the density of that nebula must have been extremely low. If we suppose the nebula to have been in the form of an extremely thin lens, the extreme thickness being not more than twice the present diameter of the sun, then if it were homogeneous and filled the space within Neptune's orbit, its density could not have been more than $\frac{1}{100,000}$ that of air at sea-level. The nebula

would undoubedly be more dense at its centre than at the edge, and so Neptune's ring could not have been even so dense as this. The matter in such a ring would be widely scattered and would probably resemble somewhat the matter in the tail of a comet. The mutual gravitation between the various parts of the ring would be extremely feeble. There would be no tendency for it to condense into a planet; on the contrary, the action of any forces that we know of would tend to dissipate it still further.

Our present knowledge of the properties of matter makes it seem extremely improbable that a planet could ever have been evolved from the condensation of a uniform ring of matter such as Laplace predicated. Thus while Laplace clearly demonstrated the fundamental fact that the solar system was not created in its present condition, that it has grown out of something radically different, yet he made many errors when he tried to outline the exact process by which the evolution was accomplished.

Within the past two or three years Chamberlin and Moulton have advanced a new theory as to the order and way in which the solar system has been developed. This is called by Chamberlin the "planetesimal" and by Moulton the "spiral" hypothesis. It avoids many of the difficulties, that appear fatal to the Laplacian theory and seems to give a reasonable and a possible outline of the manner in which the solar system may have been developed into its present complex state.

Laplace assumed a vast spherical mass of intensely hot gases from which were gradually evolved the sun and planets; Moulton assumes that the solar system was begun in a great *spiral* swarm of minute moving particles, each acted upon and its motion controlled by the mutual gravitation of the entire swarm. The idea that the original form of the solar system was spiral, was suggested by the great number of spiral nebulas that are to be found in the heavens. Spiral nebulas are very numerous, ring nebulas extremely rare, if indeed there can be found a single perfect example of a Laplacian nebula. Thousands of nebulas are known; Keeler estimated that over one hundred thousand could be photographed by the Crossley reflector of the Lick Observatory and he found the spiral to be the normal type. In nearly every photograph the spiral form can be distinctly traced.

These spiral nebulas are extremely irregular, although in many cases two distinct arms can be traced. These arms, however, are not smooth; they are broken and irregular and show large spots of dense matter, or secondary nuclei. The photographs are instinct with motion, the nebulas all appear to be whirling around and around. This whirling motion carries each particle of matter in an independent orbit about the centre; the matter moves across, not along the arms of the spiral. The particles near the centre move in smaller orbits and much faster than those near the outer edge, and with growing age the spiral changes its form and shape.

From some such irregular spiral the solar system, according to the new theory, was gradually evolved. The planets are all of the same age, they have grown out of various nuclei which existed in the original spiral. Each nucleus, as it revolved about the central mass, attracted to itself smaller particles, whose orbits crossed or passed near its path. That nucleus

FIG. 32. SPIRAL NEBULA, MESSIER 51.
Photographed with the Crossley Reflector at the Lick Observatory.

grew the faster whose path led it through regions rich in fine material.

The life histories of the great and small planets are upon this spiral hypothesis, radically different. The small planets have been evolved from small nuclei, the large planets from nuclei originally large. Owing to the very smallness of their masses, the

smaller nuclei grew but slowly and could not retain their lighter gases. They cooled rapidly and in a comparatively short time became solid bodies, without sensible atmospheres. As they cooled, they shrank in size, and this shrinkage produced internal heat, which fused the interior and liberated the atmospheric gases from the heated and compressed rocks. Planetoids and bodies smaller than Mercury never had any real atmosphere; the atmosphere of the earth was probably squeezed out from its interior after it reached its present size.

The great planets, on the other hand, have always been large; they were evolved from great nuclei. Because of their great original mass they retained their gaseous envelopes, lost their heat slowly, and have not contracted to any great extent.

In the original spiral the planetary nuclei were accompanied by smaller nuclei, which developed into the present satellites. The non-uniformity in the motions of these bodies, the retrograde motions of the ninth satellite of Saturn and of the lone satellite of Neptune, and the rapid flight of Phobos, are all accounted for by Moulton on the non-symmetrical arrangement of the original nebula. He finds no valid reason for presupposing uniformity of revolution and of development in the embryo satellite systems. Mars and its system differed from the start from Saturn and its system: and thus differing in the beginning the evolution of the two systems proceeded along different lines.

Not content with tracing the probable evolution of our system from a spiral nebula, Chamberlin attempts to carry his historical researches still further into the realms of the past and to account for the origin of the spiral itself. In the near approach of two suns as they wander through space he finds the explanation of the spiral form. Observation shows us that the countless stars are all in motion, that they are moving in different directions and with widely differing speeds. While ordinarily separated by enormous distances, still in the course of ages star must ultimately approach star and collisions must result. Far more frequent than actual collision, however, will be the close approach of star to star. During such approach each body is subjected to terrific tidal strains, and immense masses are torn from each and thrown into space, where the mutual attractions of the two stars cause these detached masses to travel in elliptic orbits about the body from which they were ejected. Just as the moon causes two tides upon the earth, one where she is overhead and one where she is underfoot, so in each star there will be ejected two great tidal streams of matter, and these streams become the two arms of a spiral. And thus the two stars, as they whirl by each other, will be converted into two great spiral nebulas.

Such is the "spiral hypothesis," the latest working theory in regard to the origin and development of the solar system. It explains many of the difficulties encountered by the "Laplacian" or "nebular

hypothesis," and it is undoubtedly the most satisfactory theory yet advanced. But it must always be remembered that it is only an hypothesis, a shrewd guess. The solar system has been developed from some simple form, from something quite different from what it is to-day; that much is certain. But what the original form was and by what exact processes the many bodies, with their intricate motions, were evolved is not known and never can be definitely known.

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